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Development of Improved Method for Measurement of Spectral Irradiance from Solar Simulators

Progress and Status as of July 31, 1964

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U.S. DEPARTMENT OF COMMERCE
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Measurement of the Spectral Irradiance from Solar Simulators

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I. INTRODUCTION

The possibility of the application of existing radiometric techniques to the measurement of the spectral irradiance from solar simulators was critically examined from a number of points of view, as regards both instrumentation and methods for evaluating the radiation data. Each component was evaluated in terms of its physical capabilities and the degree of accuracy to be expected through its use. Many of the conventional radiometric techniques and instrumentations were found inadequate in one or more respects. Some of these will be discussed. First, however, consideration will be given to detectors and some of their characteristics and shortcomings since all radiometric instrumentation includes a detector in some form as a basic component. Next a review will be given covering previously available and new standards of radiance and irradiance having possible use in solar simulation evaluation, and finally there will follow a summary covering available instrumentation and methods.

II. Detectors

Only those detectors showing most promise of usefulness in this field are considered, namely surface thermopiles, photomultipliers, phototubes, and PbS cells. The specific characteristics of detectors determine their value in accurate radiometric measurements and further determine in great part the design of the instrumentation to be employed with them. The discussions will be centered around those factors having most importance in their use in radiometry.

1. Thermopiles and Thermocouples

The usual commercial thermopile or thermocouple consists of a flat surface (usually gold or silver foil or thin sheet) coated with one of the common blacks, such as gold black, platinum black, carbon black, camphor black, or graphite (Parsons' black is also available) and in a layer whose thickness is inversely proportional to the "speed" required. The end result is usually an element having selective spectral sensitivity and varying widely in sensitivity over its surface. Both of these sensitivities usually vary additionally with the mode of measurement because of detector time response or because of the inherent characteristics of the associated electronics. Figures 1 to 4 illustrate the observed variations in sensitivity over the surface of a particular gold black, rapid response, linear surface thermopile when it was scanned by a fine line of incandescent lamp flux (set at right angles to the long dimension of the receiver) and moved slowly lengthwise with the thermopile[1/]. For figure 1 the dc output of the thermopile was measured with a Keithley "millimicrovoltmeter". For

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[1/] The thermoelectric detector was mounted with its receiving (see bottom p.2)

figure 2 the light beam was chopped at 10 cps and the thermoelectric output was amplified by a Farrand 7-10 cycle tuned ac amplifier, then rectified by means of a conventional diode (6H6) before feeding into the standard L & N strip chart recorder. Tracings taken with the light beam chopped at 7 or 13 cps differed but little from that shown in figure 2. For figures 3 and 4 the light beam was chopped at 10 and 13 cps respectively and the thermoelectric output amplified by a Perkin-Elmer Model 107 synchronous-rectifier amplifier. Other tracings were taken at higher, lower and intermediate frequencies. Similar tracings were taken at a fixed frequency, but with the phase angle of the signal changed by advancing or retarding the chopper blade relative to the commutator. It was found that for this thermopile a change of chopper speed from 10 to 13 cps produced a similar change in the tracing to that for a shift of about 30° in the chopper blade setting. It was also found that for any selected position on the thermopile receiver the magnitude and sign of the output signal went completely through a sine curve as the chopper blade was rotated 360° (or that the signal changed from the maximum value positive, to maximum value negative in 180°). Since this amplifier is highly sensitive to phase changes within the signal, any signal delay resulting because of coating thickness, variation in coating depth of radiation absorption, or time of heat conduction through the receiver element to the thermal junction, will be reflected in the magnitude and polarity of the recorded value. Hence, thermopile surfaces may be expected to vary greatly - which they do as illustrated in figures 3 and 4. From these figures alone even the number of thermojunctions in this detector could not be ascertained. Nor do all thermopiles perform alike.

In figures 5, 6, 7 and 8 similar data are given for a gold-black thermopile having a somewhat slower response. Again the dc, and the ac measurements with a conventional amplifier, show close similarities (it is to be noted that the scanning directions for the dc curve is reversed). But the data in figures 7 and 8, wherein the signal was chopped at 10 and 13 cps and a synchronous-rectifier amplifier was employed, are markedly different. Nothing in the illustrations serves to identify this as a 4-junction thermopile. However, when the chopping frequency was set at 16 cps and 7 cps respectively, the records indicated that the detector has 4 junctions with the reading positive and negative respectively relative to the curves shown in figures 7 and 8. Data on other thermopiles we have examined (1,2)[2/] follow similar lines to those illustrated here.

1/(Continued) surface perpendicular to the flux beam on a motor driven carriage immediately back of a fixed narrow slit. The carriage was moved horizontally (with the slit vertical, and the detector with its long dimension horizontal) by means of a synchronous motor gear and screw drive at a speed of 1/12 inch per minute. This corresponds to a detector movement or scanning rate of 1/48 inch (0.021 inch or 0.53 mm) per abscissa scale division on figures 1 to 8 since the scanning time for each scale division was 15 seconds.

2/Figures in parentheses indicate the literature references at the end of this report.

The spectral response of blackened thermal detectors depends upon a number of factors, but probably most of all upon the "blackness" of the coating employed. When this investigation began no standard in this area existed. However, at present the nearest approach appears to be a conical cavity (see figure 9) blackened inside with a thin coating of a highly efficient absorber. Smoked-on camphor black has been found to be superior to carbon black or gold black. Since the cavity detector coated with camphor black is spectrally "flat" or neutral relative to Parsons' black, at least from the ultraviolet to about 20 microns, we have reason to believe that a cavity detector coated with camphor black is non-selective with wavelength over this spectral region. All commercial thermopiles we have compared with this conical detector (except those coated with Parsons' black) show decreases in response at the longer wavelengths relative to that in the ultraviolet and visible spectrum. Figure 10 shows the relative spectral response of an Eppley carbon-black (round disk) surface thermopile as compared with our standard No. 3 cavity detector. Other carbon-black units had similar response curves. In figure 11 is illustrated the spectral response of a Reeder linear gold-black surface thermopile. The upper curve is for data taken with the dc output measured with a Keithley "millimicro-voltmeter". The lower curve was obtained with the light beam chopped at 13 cps and the thermoelectric signal measured through the use of a Perkin-Elmer Model 107 synchronous-rectifier amplifier. No spectral measurements were made by using conventional ac amplification, but it is expected that the results would lie between those recorded for the other two systems.

2. Photomultipliers

Much has been written on photomultipliers and their use in the precise measurement of radiant flux (3-5). The fact that the dark current characteristic may be a problem in dc measurements is well established as is also that noise increases greatly with temperature and as the sensitivity is extended to longer wavelengths. To minimize these effects in the present investigation only those multipliers having their sensitivity confined to the ultraviolet and visible spectral regions are considered. Representative of this group of detectors are the RCA 1P-28, the ASCOP 541A-05 and EMI types 6256B and 9592B. Each has a type S-5 surface or a surface of similar character. Their responses may be expected to be linear only within specified voltage and current limits. Their sensitivities may be adjusted over wide ranges by varying the applied voltage; but this has the disadvantage that slight voltage fluctuations produce erratic results. Hence, in accurate radiometric work, the high voltage power supply must have a very constant output regulation.

An additional characteristic of all photomultipliers examined is their variation in sensitivity over their surfaces. This may result in part from optical imperfections in the multiplier window. We found the window effect large with an EMI cell type 9592B. But the character of the cathode surface primarily controls this factor. In figures 11 and 12 are shown the variations in sensitivity of two photomultipliers (an RCA 1P-28 and an ASCOP 541A-05) when a narrow beam of monochromatic flux from the exit slit of a spectrometer is scanned across their cathodes[3/]. Measurements on these multipliers at different wavelengths resulted in similar curves. However, some multipliers have been found to vary significantly in spectral sensitivity (1) over their cathode surfaces.

[3/] To obtain the data on the variations in sensitivity of the various photoelectric detectors illustrated in figures 12, 13, 16, 18 and 19, the vernier screw incorporated for adjusting the horizontal detector positions was driven by a 1 rpm synchronous motor so that each detector moved across the exit slit of the monochromator at a very slow rate. For all the detectors except those of figure 13 the vernier screw had 20 threads per inch and the resulting detector movement was 1/20 inch per minute. This corresponded to 1/80 inch (0.0125 inch or 0.32 mm) movement along (or across) the detectors per abscissa scale division in figures 12, 16, 18, and 19. The movement in figure 13 was about 4 times this value, resulting in a greatly compressed curve.

3. Phototubes

Since phototubes and photomultipliers are basically the same as regards cathodes much of the above discussion also applies to phototubes. Hence, their best use in this project applies principally to the ultra-violet and visible spectrum with the type S-4 or S-5 surface tubes. The RCA-type 935 is a representative tube of this class (see figure 15 for a typical spectral response curve) and has been found to be extremely useful when the higher sensitivity of the multiplier is not required. Furthermore, use of a vacuum phototube eliminates the need for a carefully controlled high voltage supply. In its use, however, some problem is involved in eliminating the shadow effect of the anode. This is illustrated in figure 16 in which a crosswise scanning of the cathode sensitivity of a typical type 935 tube is displayed.

4. PbS Cells

No attempt will be made to cover all the characteristics of PbS cells. Much data may be found elsewhere (3, 6, 7, 8, 9) on this subject. They vary not only in spectral sensitivity but also over their surfaces. Figure 17 illustrates a typical spectral response curve for one of these cells. Figures 18 and 19 illustrate variations in sensitivity over the surface of a particular cell as it is scanned crosswise and lengthwise by a narrow beam of monochromatic flux. It is noted that for this cell a higher sensitivity is obtained (contrary to expectation) when the flux line is set at right angles to the line joining the two electrodes.

In the present investigation, in order to eliminate the short term effects of temperature and humidity changes on the PbS cells, they have been enclosed and hermetically sealed in massive brass cylinders having quartz glass windows. And to eliminate the effects of the large "dark" currents the measurements are made with the flux beam chopped at 510 cps and the PbS cell output amplified through the use of a special tuned amplifier (10), which will be discussed in greater detail later.

III. Radiometric Standards

The investigation of instrumentation for use in measuring the output of solar simulators has included the use of a number of radiometric and photometric standards. Primary among these is the standard of spectral irradiance (11,12). But also included are those of spectral radiance (13), total irradiance (14-17) and luminance (18). All are based upon the radiance of a blackbody as defined by the Stefan-Boltzmann and Planck laws of radiation and their accuracy is dependent upon the validity of these laws and the care with which the various transformations have been made (See references 1 and 8 - 14).

1. Standard of Total Irradiance

The NBS standard of total irradiance consists of a carbon-filament lamp operated at a temperature around 1600 to 2200°K. At these temperatures most of the irradiance falls between the wavelengths of about 1 and 3 microns. This standard was set up through comparisons of the irradiances from a group of lamps with the irradiance from a blackbody (14,15). For this work the blackbody temperature was usually set at approximately 1400°K and a thermopile heavily coated with lampblack was employed as detector. Such a heavily coated thermopile has been found to be closely uniform in sensitivity with wavelength between the visible and about 3 microns in the infrared, and hence will give an acceptably accurate evaluation of an 1800°K lamp filament in terms of a 1400°K blackbody. Our recent reviews of detectors substantiate the validity of the earlier measurements in this area, so that the carbon-filament lamp standard of total irradiance is an adequate standard for use in the calibration of properly blackened thermal detectors over the range from a few microwatts to several hundred microwatts per cm^2. To cover higher ranges of irradiance, work is in progress toward setting up a secondary standard yielding an irradiance approximating 100 to 150 milliwatts per cm^2.

2. Standard of Spectral Radiance

Two standards of spectral radiance have been set up to cover the region of 0.25 to 2.6 microns (See figure 20). These were set up independently through the use of two blackbodies having temperatures of about 2200 to 2600°K and 1200 to 1400°K respectively. This work has been described in detail elsewhere (13). One of the setups employed is shown in figure 21. The experimental work consisted of alternately allowing the radiation from the blackbody (set at a specific temperature) and the lamp (set at a specific current) to enter a spectroradiometer after being focussed onto the entrance slit by the same optical system, and measuring the relative radiances of the two sources at selected wavelengths. For the system illustrated the wavelength range was 0.25 to 0.75 micron, and a 1P-28 photomultiplier was used as the detector. A supplementary set-up consisting of similar optics and electronics and a 1400°K blackbody covered the spectral range of 0.5 to 2.6 microns. In this case an Eastman Kodak PbS cell, supplemented by an RCA 7102 photomultiplier, was employed as detector. Thus the spectral radiances of two groups of strip lamps were evaluated in terms of the two blackbodies at specific temperatures as defined by the Planck law of radiation. Although set up independently, the two standards are in close agreement over the common spectral range of 0.5 to 0.75 micron. The two standards are simply combined in one strip lamp set at a single current (35 amperes) to cover the complete range from 0.25 to 2.6 microns.

3. Standard of Spectral Irradiance

The experimental work connected with setting up the standard of spectral irradiance (see fig. 22) offered an opportunity to check the agreement between the existing standards of spectral radiance, total irradiance, and luminous intensity. Although consideration was given to setting up this new standard directly against a blackbody, a number of difficulties involved in that procedure led us to set it up through comparisons with the standards of spectral radiance supplemented by measurements against the standards of total irradiance and of luminous intensity, all three of which had been established through direct comparisons with the radiances from blackbodies at specific temperatures. This work is described in detail elsewhere (11). The results indicated close agreement between these standards, in some cases to 1 percent and certainly in all cases to within a few percent. Hence, all the NBS standards in this area are based upon the radiance of the blackbody as defined by the Planck and Stefan-Boltzmann laws of radiation.

The original standard of spectral irradiance as described in reference 8 is a 200-watt coiled-coil tungsten-filament quartz-iodine lamp. Recently, this has been supplemented by a similar ~~high silica glass~~ lamp of 1000 watt (120 volt) commercial rating. The new standard was set up through independent measurements by two laboratory groups using dissimilar equipment. In one case integrating spheres were placed at the entrance slit of the spectroradiometer and the output signal evaluated by dc instrumentation. In the other the lamps (both the 200-watt quartz-iodine standards and the new 1000-watt lamps) were carefully placed in front of the entrance slit without the use of integrating spheres, the light beam chopped at 510 cps, and the photoelectric output measured through the use of a 510 cps tuned amplifier and ac VTVM. The averages of the data on four 1000-watt lamps as compared with several (3 to 4 in each case) 200-watt standards were in agreement to within about one percent, although individual variations at specific wavelengths amounted to as much as several percent. The data for two of the 1000-watt tungsten-iodine lamps are given in table I. These data are for a distance of 1.0 meter when the lamps are operated at 8.50 amperes. It was ascertained that the inverse-square law applied at 50 cm with immeasurable error, so that these values may be multiplied by 4 and the lamps operated at that distance. Small corrections may be required when the lamps are operated at lesser distances. The mean spectral values for the four lamps are tabulated in table 1 for use in establishing the effective transmission character of the filters used in the filter spectroradiometer described in a later section of this report.

IV. Instrumentation and Methods of Solar Simulation Measurement

Under this heading we shall discuss only those instruments and methods that we have examined that are considered to have some potential value in connection with solar simulator measurements. First of all, a semi-portable type of equipment appears as a prime requirement. Hence, compactness is at a premium, and cost is a secondary consideration - but important since there are many simulators located in various laboratories to be measured or monitored. Second, but of greatest importance is that of accuracy of measurement. This is triply difficult since the radiation from the solar simulator not only differs from that of the standard lamp in spectral quality and intensity but also in apparent size of source. All these factors and others, in particular detector characteristics, must be taken into account in the choice or design of equipment and methods of measurement. Three systems are described, one of which employs more or less conventional spectroradiometric equipment and two of which employ filter spectroradiometers.

1. The Spectroradiometric Method

In order to measure the spectral distribution of radiation over the solar spectral region (0.30 to 2.5 microns) the nimimum requirement in the instrumentation is the incorporation of a double monochromator (10). With the spectral range extended to the region of 0.25 micron the problem of scattered radiation becomes more difficult by a factor of at least 10 (see table 1), since the available standards have an emission at 0.25 micron only one-tenth that at 0.30 micron. The spectral intensity of the solar simulator can also be expected to be at a lower level at 0.25 micron. Hence, the instrumentation chosen must have very low scattering at this wavelength. The underlying principles of grating and prism instruments rule in favor of the prism on several counts. First of all, the grating will scatter a lot of flux since the grooves are not highly polished. Then there is the problem of multiple orders of spectra, ghosts, and other erratic phenomena associated with gratings. Finally, there is the difficulty of satisfactorily extending the data over the full spectral range with a single grating. These difficulties can easily be averted through the use of good optical-quality prisms (in this case quartz). Hence, our choice has been a double-quartz-prism spectroradiometer.

a. Monochromator

Double-prism spectrometers are available from a number of sources, although complete spectroradiometers are not readily obtainable from any manufacturer, domestic or foreign. For compactness, portability, economy and adaptability for use over wide spectral regions through the choice of prisms, the Carl Leiss double monochromator was selected as the basic unit in the conventional spectroradiometer set-up method for the measurement of the spectral irradiance of solar simulators. The optical layout of this instrument, together with the various auxiliary components forming the complete spectroradiometer are shown in figure 23. Quartz prisms have been selected to cover the spectral range of 0.25 to 2.6 microns.

This double monochromator contains aluminized mirror optics making it possible to operate over an extended wavelength interval (limited only by the prism material) without change in focus or mechanical slit width. The resolving power of this instrument is relatively high - even above any present requirements in solar simulator measurements - and the light output has a high spectral purity and high degree of freedom from scattered radiation. The instrument is extraordinarily compact and light in weight making it easily adaptable for mounting on an optical bench (a light duty lathe bed). This requirement is important to permit rapid change in observations between solar simulator and standard lamp. Previous use of this instrument on lathe beds in this and other laboratories (13, 19) had proven the advantages of this system.

In this instrument a single wavelength drum is geared with linkage controls which rotate the two prisms thus making possible a slow continuous scan through the spectrum. A 3-speed reversible synchronous motor drive has been constructed and geared to the wavelength drum. During each revolution of the wavelength drum three unevenly-spaced contacts have been built into the mechanical drive for purposes of producing wavelength index marks on the recorder chart. The other auxiliary components of the spectroradiometer are discussed under the following captions.

b. Detectors

In order to cover the full spectral range from 0.25 to 2.6 microns efficiently at least two photoelectric detectors are required. As a result of the studies on detectors discussed above a high sensitivity, low noise, photomultiplier was chosen to cover the ultraviolet and visible spectral ranges. An Eastman Kodak PbS cell (0.5 or 1.0 x 1.0 cm) was selected to cover the visible and infrared spectral regions. One detector of each type was mounted on an adjustable table so that by means of a vernier screw either could alternately be brought into proper horizontal position back of the spectrometer slit after the detector box (housing) was mounted onto the instrument and adjusted for correct vertical position. The correct position for each detector was found by setting it for maximum deflection at the wavelength of maximum instrumental output. This precaution eliminates errors resulting from the small wavelength range within the exit light beam. Several pairs of detectors have been mounted in this manner. Among the different types of photomultipliers employed are the ASCOP 541A-05, the RCA 1P-28, and the EMI 6256B and 9592B. Variations in sensitivity across the surfaces of some of the detectors in these four boxes are illustrated in figures 12, 13, 18 and 19.

c. Diffusing Optics

In the measurement of the spectral irradiance of a source the characteristics of both the detector and the monochromator employed are highly important. Primary among these characteristics are uniformity of sensitivity over the detector surface and uniformity of transmittance over the full aperture of the monochromator if the instrumentation is to be employed in the conventional manner without difusing optics. However, as noted above, no available detector meets these requirements. Nor is there a monochromator manufactured anywhere that meets these specifications. The spectrum produced is distorted in a number of ways, especially in a double monochromator. Not only are certain regions of the spectrum more compressed than others, but we have polarization effects, selective absorption, mechanical defects of spectral drive between the two sections of the instrument, imperfect optics, imperfect achromatism, scattered radiation, and possibly other effects which result in the flux beam at the exit slit emerging in an uneven pattern covering an area much larger than the first and second defining slits of the instrument.

When consideration is given to the large variations that may exist over the surfaces of detectors, coupled with the non-uniformity of the emergent beam of the spectroradiometer, the direct comparison of sources spectroradiometrically becomes very difficult. For example, with one detector source A may appear to have several times the intensity of source B at a set wavelength. With a change of detector (or even with a resetting of the original detector) a new measurement may indicate just the opposite - that source B has several times the intensity of source A at the set wavelength. Even with very careful optical adjustments using two similar sources (two lamps of the same type and size) errors of 50 to 100 percent may occur. With sources of unlike size and shape accurate comparisons are impossible by direct radiometric comparison without auxiliary equipment.

Accurate comparisons between like sources (two lamps of the same type for example) may be made spectroradiometrically by the use of detectors having surfaces of uniform sensitivity provided each lamp is set to irradiate the spectroradiometer in exactly the same way. This may be simply accomplished through the use of identical auxiliary optics as shown in figure 21 in radiance measurements but in irradiance work the difficulty is greater.

Even the small differences in filament shapes between two lamps of the same type may be sufficient to upset the measurements by many percent. However, in practice the two lamps may be individually set at the optimum position by observing the radiometric deflection and setting each of the lamps (individually) at the position for maximum reading after the detector has been mounted with its position of maximum sensitivity centered on the slit and the wavelength drum of the spectroradiometer has been set for peak response for the particular lamp and detector. With these precautions two like sources may be compared accurately, the same results being obtainable with different detectors.

But when the sources are different - as will usually be the case with an unknown source being measured in terms of a standard - the results will depend greatly upon the experimental set-up. With radiance measurements, the results will simply be relative for a particular area of the unknown - as for example - a limited section of the arc between the electrodes of a xenon arc. Such a result is of little value for most purposes. A more meaningful measurement must include the entire source- and will usually require that it be made in terms of irradiance. Since the two sources, the standard and unknown, are of different geometrical shape and area as viewed from the spectroradiometer slit, some optical method must be included to produce like sources as seen from the spectrometer. This can best be accomplished through the use of a diffusing sphere or spheres which are alternately illuminated by the two sources. This is not a new idea (20 - 24) but one which is often by-passed if sufficiently useful information can be had without resorting to its use. For a sphere coating, MgO offers good reflectance from about 0.25 to 1.6 microns (25 - 28) and is usable to about 11 microns. At wavelengths longer than about 1.6 microns, metallic surfaces are probably best. Some of the ceramics appear promising if methods of coating or casting can be worked out. In lieu of spheres, for approximate measurements, good diffusing surfaces may be employed and set such that the diffusing surface receives and reflects or transmits the radiant energy in the same manner in the two cases if sufficient energy is available.

In figures 24 and 25 data are given showing what may be expected through the use of certain (reflecting) diffusing surfaces used inside spheres, or as flat plates. Our search of the literature has revealed nothing better than these materials for this purpose. Transmitting diffusers were eliminated from use because the available information indicated their inferiority as regards cosine response.

In figure 24 is shown the relative spectral response curve obtained over the lead sulphide region when a 1000-watt tungsten-quartz-iodine lamp is placed 12 inches from a 4" sphere coated with MgO, a 4" sphere with an evaporated gold coating, a $MgCO_3$ block, and a MgO ceramic disk. For each curve the sensitivity of the PbS detector, the spectral irradiance from the lamp, and the monochromatic parameters remained constant. Therefore, the curves give an indication of the relative spectral efficiencies of the diffusers for their combined instrumentation, detector and source.

Similarly, figure 25 shows the results when the same procedure is followed for three of the four diffusers from 0.25 - .8 micron. In this case an EMI 9592B photomultiplier was the detector employed. Incidentally, the resolution of the monochromator for this work ranged from about 1.5 nm at .3 micron to about 8 nm at 1.5 microns.

MgO as smoked onto the inside of a sphere is highly fragile, but with care its use is quite satisfactory for wavelengths shorter than about 1.5 or 1.6 microns. At longer wavelengths a sphere first blasted with small glass shot (diameter about 0.0017 to 0.0029 inch) giving a depth of roughness of around 100 micro-inches and then coated with evaporated gold (2 opaque) has been found superior.

$MgCO_3$ in block or plate form and used as a flat reflecting surface has a high efficiency through most of the solar spectral region. It shows some drop in the ultraviolet and in the infrared, however. A ceramic disk cast of MgO approximates the efficiency of $MgCO_3$ in the ultraviolet and visible but is superior in the infrared spectral region. The ceramic disk is furthermore much more rigid and can be handled with less care without damage.

As indicated in figures 24 and 25 the efficiency of a flat plate diffuser is about 10 times that of the best integrating sphere. It has other disadvantages, however, which over-rule its use. Distance measurement from the plate diffuser to the standard is indefinite. Also, since in the solar simulator measurements the standard must be placed in close proximity to the spectroradiometer, this error may amount to several percent. Furthermore, the use of screens to reduce solar simulator irradiance to near that of the standard offers problems as does also the proper equivalent shielding of the reflector block for both the standard lamp and the solar simulator. Because of these difficulties we have chosen and recommend the use of the integrating spheres in solar simulator measurements.

Calculations indicated that for use with an instrument having an aperture approximating that of the Carl Leiss monochromator, the most efficient integrating sphere size was of the order of 3 to 4 inches in diameter (29). Tests were accordingly made with the two sizes (3" and 4") and it was found that the two were roughly equally efficient. Since the 4-inch sphere was at the time more readily available and it offered a larger reflecting surface, hence should produce less error because of small inequalities in reflectivity, that size was chosen for use in this project.

d. Amplifiers and Power Supplies

The use of integrating spheres at the entrance slit of the spectroradiometer reduces the flux entering the monochromator by a factor of about 1000. This means that severe requirements are at once placed upon the electronics of the system. Phototubes and thermopiles are too insensitive and need no further consideration for use in this instrumentation. Only photomultipliers are adequate for use in the ultraviolet and visible regions of the spectrum, and these require the best available power supplies and amplifiers. Various systems were reviewed or tried out. Best results to date have been obtained by using either a Keithley **pico-ammeter** in dc operation or, with chopped signals, a special custom-built 510 cps ac amplifier (described in some detail elsewhere (10). This amplifier is not commercially available but may be easily constructed by using 5 to 10 percent tolerance electronic components. A circuit diagram of it (incorporating a few minor improvements over that shown in reference 10 for use with a 935 type phototube is given in figure 26. For use with PbS cells or photomultipliers the switch marked "S" is simply moved to the closed position. The 510 cps tuned amplifier is superior to the dc instrument in relation to errors because of dark current and since it is a more rugged instrument it has been chosen for use in this project - unless tests on a new tuned lock-in amplifier (30, 31) now under study indicate the latter instrument to be superior.

For use in the infrared spectral region between about 0.7 and 2.6 microns an Eastman Kodak PbS cell has been found the most suitable of any of the detectors studied. Its sensitivity is, however, lower than desired for highest accuracy. Because of its high dark currents only ac operation is satisfactory. The same 510 cps tuned amplifier is employed with this detector. As previously noted, to keep dark current effects at a minimum, we have enclosed each of the PbS cell detectors within a massive hermetically sealed brass cylinder which keeps the humidity constant and greatly attenuates temperature changes within the element.

e. Recorders and Wavelength Drives

The problem of recorders has been completely solved by the manufacturers except for the design of suitable input networks to match the output of the electronics in impedance and voltage. For use with the 510 cps amplifier a standard L&N 6 millivolt dc recorder simply required a 100 to 1 step-down potentiometer and filter network. If desired, however, the data may be taken directly from the dial of a Ballantine AC VTVM. In recording when the Keithley pico-ammeter was used the same input network worked satisfactorily.

As indicated above, contacts built into a three-speed reversible wavelength drive energize signals within the 510 cps amplifier (see figure 26) to give indications on the strip chart record at specific wavelengths. These wavelengths are determined through calibrations employing mercury and other arc sources such as argon, neon, krypton and cesium.. Three speeds (forward or reverse) permit scanning the spectrum at rapid, medium, and slow rates as may be required by the type of spectrum or degree of structure required.

f. Filter Spectroradiometric Methods

Two filter spectroradiometric methods have been investigated, namely, photoelectric and thermoelectric. Both employ the same type of interference filters. In the photoelectric method wherein phototubes and PbS cells are employed the solar simulator is simply compared, wavelength by wavelength, with the 1000-watt tungsten iodine lamp standard of spectral irradiance. This method eliminates the need for a knowledge of the absolute sensitivity of the detectors or the transmittance of the filters, except for their relative spectral characteristics. In the thermoelectric method, thermopiles (or thermocouples) having known spectral sensitivities are calibrated in terms of a standard of total irradiance. In this method the absolute transmittances of the filters are required also.

1. Photoelectric Filter Spectroradiometer

The photoelectric filter spectroradiometer consists primarily of approximately 30 interference filters, a phototube (type RCA 935 or equivalent), and a PbS cell in a housing of the type described above for use with a monochromator and similarly arranged on an adjustable table so that either detector may be placed in proper position by a vernier control. The interference filters are placed in "slide" boxes and fitted into a mechanism constructed after the design of a hand operated slide projector such that any filter may be readily pushed into position between the standard lamp and the detector. As in the commercial projector a screen cuts off the incident beam when no filter is in place thereby protecting the photoelectric detector from injury. To facilitate alternate measurements on the solar simulator and standard lamp, the detector housing plus filter changing and light chopping mechanisms are mounted on an optical bench and arranged for rapid interchange of position between the two sources. We have found a lathe bed with end stops set at operating positions highly satisfactory for this instrumentation.

While it may not be necessary to use an integrating sphere in this instrument, such use is to be recommended since small errors in measurement result because of variations in detector surface sensitivity and aperture effects, and because of difficulties in ascertaining the true distance to the detector itself and in attenuating the solar simulator beam relative to that from the standard lamp. A MgO coated sphere has accordingly been incorporated into the instrument. Although its efficiency for wavelengths longer than about 1.6 microns falls below that for the gold sphere, it is nevertheless satisfactory since relatively high fluxes are transmitted through the interference filters at these wavelengths.

The electronics employed in this filter spectroradiometer consist of a duplicate 510 cps amplifier and a Ballantine ac VTVM. The RCA-935 phototube and Eastman Kodak PbS cell have sufficient sensitivity for obtaining strong signals, relatively free of noise since the interference filters (produced by Optical Coating Laboratory and Thin Films Products Inc.) employed are not only highly efficient in eliminating radiation outside the selected transmission bands, but have high transmittances within the narrow bands isolated. Representative curves for three of the filters are given in figures 27, 28 and 29.

The "effective wavelength" for each of the filters employed, which depends not only upon the particular spectral transmittance of the filter but also upon the spectral energy distribution of the particular source and upon the spectral response of the particular photoelectric detector in use, is found as follows. First the spectral transmittance of the filter is carefully determined with a Model 14R Cary spectrophotometer. This curve is characteristic of the filter and is used in the calculations regardless of the source or detector employed. In the photoelectric spectroradiometric method high accuracy is required only in the determination of relative values as a function of wavelength. However, since accurate absolute values are required in the thermoelectric filter spectroradiometric method, the spectral transmittance measurements are made with great care (see figures 27, 28 and 29). Then the relative spectral response of each detector is determined and plotted through that spectral range in which it is employed. Then the data for the spectral energy distribution of the standard lamp are plotted in detail for the spectral region of transmittance for each filter. Finally, at close uniformly-spaced spectral intervals, products of the ordinates of these three curves are taken and summed. The wavelength on the two sides of which these sums are equal is taken to be the effective wavelength for each filter-detector-standard-source combination. Except for small corrections which may be required because of marked differences in spectral quality between the standard lamp and the solar simulator source under investigation these effective wavelengths are employed in obtaining points on the spectral solar simulator curve in terms of the standard lamp curve from the ratios of readings of the measured flux from the two sources. Any corrections are expected to be small or insignificant except in the vicinity of strong line or band emission since each filter covers a very narrow spectral region.

In practice it may be difficult to obtain by spectroradiometric means the relative spectral response of the specific phototube or PbS cell employed in this work. Fortunately we do not have to determine the curve in this way. The relative spectral response can better be obtained by filter measurements (32 - 34). First, an approximate spectral response is assumed. (See figures 9B, 10 and 12). Then by employing the values for the spectral irradiance of the standard lamp (see table 1) and the values for the spectral transmittance of the different filters (see figures 27, 28 and 29) comparisons are made between the calculated integrated responses and those observed when using the different filters. Absolute values need not be employed since only a relative spectral response curve is required. Hence, the observed reading at a set wavelength may be adjusted to an arbitrary scale value and the spectral response at other wavelengths evaluated by a trial and error method of calculation. The relative spectral responses of the particular photoelectric detectors employed having been obtained in this manner, they are ready for use in solar simulator measurements.

2. Thermoelectric Filter Spectroradiometer

This method is similar to that employed by Drummond et al (35) in that a thermopile (or thermocouple) calibrated by the use of a standard of total irradiance is employed as detector. The same set of interference filters as employed in the photoelectric spectrophotometer is satisfactory except that those filters which are not completely "blocked" in the infrared must be either eliminated or used with additional blocking. The total flux transmittances of these filters are relatively low, especially in the ultraviolet and visible regions of the spectrum thereby requiring high amplification of a thermoelectric signal. The combined use of both the "spectrally flat" cavity detector (calibrated in volts per watt-cm^{-2} through the use of a carbon filament lamp standard of total irradiance) and a Keithley nanovoltmeter should give acceptable results. However, most of our effort to date has been directed toward the development of the conventional spectroradiometric and photoelectric filter spectroradiometric methods of solar simulator measurement.

V. Concluding Remarks

In the foregoing paragraphs we have outlined the instrumentation and procedures covering three practical methods for use in the measurement of the spectral flux distribution of solar simulators. In developing the instrumentation and methods we have made extensive studies of detectors of various types and have obtained a considerable amount of data of a type not readily available elsewhere on those detectors best suited for this type of work. Much consideration was given to detector characteristics in the choice of instrument design. Emphasis was placed upon those designs which are best suited for "field type operation" under conditions which might not always be what one would best like in the laboratory. An effort was made to minimize "dark current" or "instrument drift" effects.

In conclusion, for primary use we recommend the conventional spectroradiometric method in which an integrating sphere is employed and the incident beam is chopped, permitting ac amplification for the ultraviolet, visible and near infrared region of the spectrum. For the infrared, preference is for use of the photoelectric filter spectroradiometric method. Hence, we recommend the use of the two systems - supplementary to each other. The first lacks the desired sensitivity in the infrared; the second lacks the desired spectral resolution in the ultraviolet. Used together, the two systems will give high resolution, high sensitivity, and high accuracy throughout the solar spectral region. Furthermore, both instrumentations are relatively compact so that the completed equipment can be assembled upon a single laboratory table and moved about with little difficulty. The small size and weight of the filter spectroradiometer permits it to be placed upon the prism instrument in operation, or as an independent instrument easily carried about the laboratory or transported from laboratory to laboratory.

Table I. Spectral Irradiance of 1000-Watt Tungsten-Filament Iodine Lamps in $\mu W/cm^2$-nm at a distance of 1.0 Meter.

λ, μ	QM-2	QM-4	Avg. of 4 Lamps
.25	0.0068	0.0070	.0069
.26	.0121	.0123	.0123
.27	.0203	.0205	.0204
.28	.0321	.0324	.0322
.29	.0478	.0485	.0481
.30	.0676	.0692	.0684
.32	.126	.130	.128
.35	.281	.289	.286
.37	.428	.439	.436
.40	.728	.734	.737
.45	1.38	1.40	1.40
.50	2.23	2.22	2.25
.55	3.17	3.14	3.19
.60	4.12	4.11	4.16
.65	5.03	5.03	5.08
.70	5.78	5.82	5.86
.75	6.34	6.35	6.41
.80	6.66	6.79	6.93
.90	6.85	6.79	6.93
1.00	6.65	6.57	6.71
1.10	6.20	6.13	6.25
1.20	5.62	5.55	5.66
1.30	5.03	4.95	5.05
1.40	4.46	4.38	4.47
1.50	3.94	3.86	3.95
1.60	3.45	3.38	3.45
1.70	3.00	2.95	3.01
1.80	2.60	2.55	2.63
1.90	2.25	2.19	2.25
2.00	1.94	1.89	1.94
2.10	1.69	1.65	1.69
2.20	1.48	1.45	1.48
2.30	1.32	1.29	1.32
2.40	1.19	1.16	1.19
2.50	1.09	1.06	1.09
2.60	1.02	.99	1.02

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Legends

Fig. 1. Variations in sensitivity along thermopile R-9371 as indicated when the dc output is measured.

Fig. 2. Variations in sensitivity along thermopile R-9371 as indicated when the ac output is measured with the light flux chopped at 13 cps.

Fig. 3. Variations in sensitivity along thermopile R-9371 as indicated when the ac output is amplified and measured after synchronous rectification, with the light flux chopped at 13 cps.

Fig. 4. Same as figure 3 except that the light flux is chopped at 10 cps.

Fig. 5. Variations in sensitivity along thermopile R-1 as indicated when the dc output is measured.

Fig. 6. Variations in sensitivity along thermopile R-1 as indicated when the ac output is measured with the light flux chopped at 13 cps.

Fig. 7. Variations in sensitivity along thermopile R-1 as indicated when the ac output is amplified and measured after synchronous rectification, with the light flux chopped at 13 cps.

Fig. 8. Same as figure 7 except that the light flux is chopped at 10 cps.

Fig. 9. Gold foil conical cavity detector.

Fig. 10. Relative Spectral response of a lamp black coated thermopile (Eppley No. 6246) as compared with cavity detector No. 3.

Fig. 11. Relative spectral response of a gold black coated thermopile (Reeder No. 9371) as compared with cavity detector No. 3.

Fig. 12. Variations in sensitivity of an RCA 1P-28 photomultiplier for monochromatic light flux as indicated when the cathode is moved across the exit slit of a spectroradiometer.

Fig. 13. Variations in sensitivity of an Ascop type 541A-05 photomultiplier and of an Eastman PbS cell for monochromatic light flux as indicated when their cathodes are moved across the exit slit of a spectroradiometer. These two detectors form a pair to cover the spectral range from 0.25 to 2.6 microns. Adjustment is made so that each operates at the peak of maximum sensitivity

Fig. 14. Relative Spectral response for equal energy of an Ascop type 541A-05 photomultiplier (Manfacturers' data).

Fig. 15. Relative spectral response for equal energy of an RCA type 935 phototube (NBS data on tube 935-1)

Fig. 16. Variations in sensitivity of an RCA type 935 phototube for monochromatic light flux as indicated when its cathode is moved across the exit slit of a spectroradiometer. The dip near the center of the illustration results from shadowing effects of the anode wire. This tube is employed with the major part of the surface exposed when used in the filter spectroradiometer,

Fig. 17. Relative Spectral response of an Eastman Kodak PbS cell (Manufacturers data).

Fig. 18. Variations in sensitivity for monochromatic light flux as indicated when the PbS cell is moved across the exit slit of a spectroradiometer. For this illustration the electrodes were at the top and bottom of the spectrometer slit.

Fig. 19. Same as figure 18 except that cell was rotated 90° thus placing the electrodes at right and left sides of slit respectively.

Fig. 20. Tungsten ribbon strip lamp standard of spectral radiance.

Fig. 21. Block diagram showing the instrumental setup of blackbody, monochromator, lamp, and associated equipment employed in the calibration of the NBS standard of spectral radiance for the wavelength region of 0.25 to 0.75 micron.

Fig. 22. The 200-watt Quartz-iodine lamp standard of spectral irradiance. The 1000-watt standard is of similar appearance and is mounted in a similar holder.

Fig. 23. Optical layout of Carl Leiss monochromator and block diagram of complete double prism spectroradiometer employed in solar simulator measurements.

Fig. 24. Relative efficiencies in the infrared spectrum of four diffusers when used in combination with the Carl Leiss spectroradiometer when employing an Eastman Kodak PbS cell as detector and a 1000-watt iodine lamp as source. The peak near 1.2 microns indicates maximum instrumental deflection at this wavelength. The highest value at this wavelength was arbitrarily set at 100. All lower values may be read from the curves in terms of this peak value.

Fig. 25. Same for the ultraviolet and visible spectrum as in figure 24 for the infrared except in this case the detector is an EMI type 6256B photomultiplier and the peak value is again arbitrarily set near 3000.

Fig. 26. Electronic circuit employed in the 510-cycle-per-second tuned amplifier. Resistances are in megohms and capacitances are in microfarads except as otherwise noted.

Fig. 27. Spectral transmittance of the 0.560 micron narrow-band interference filter as obtained on a Cary-Model 14R spectrophotometer.

Fig. 28. Spectral transmittance of the 1.598 micron narrow-band interference filter as obtained on a Cary Model 14R spectrophotometer.

Fig. 29. Spectral transmittance of the 1.56 micron wide-band interference filter as obtained on a Cary Model 14R spectrophotometer.

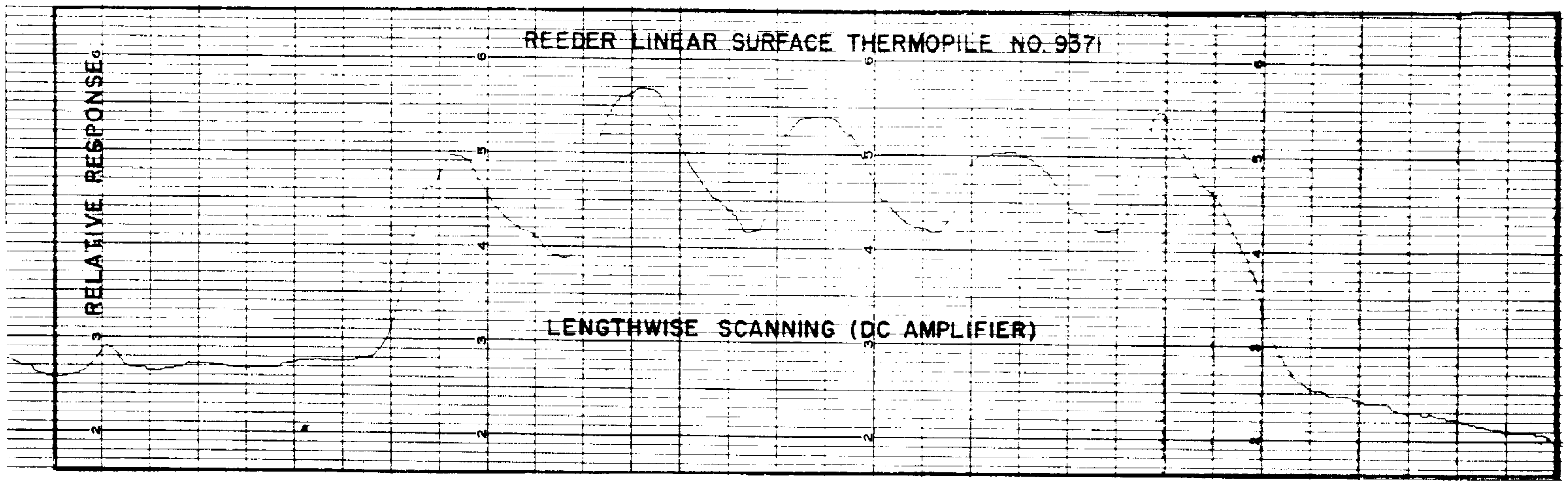


Fig. 1. Variations in sensitivity along thermopile R-9371 as indicated when the dc output is measured.

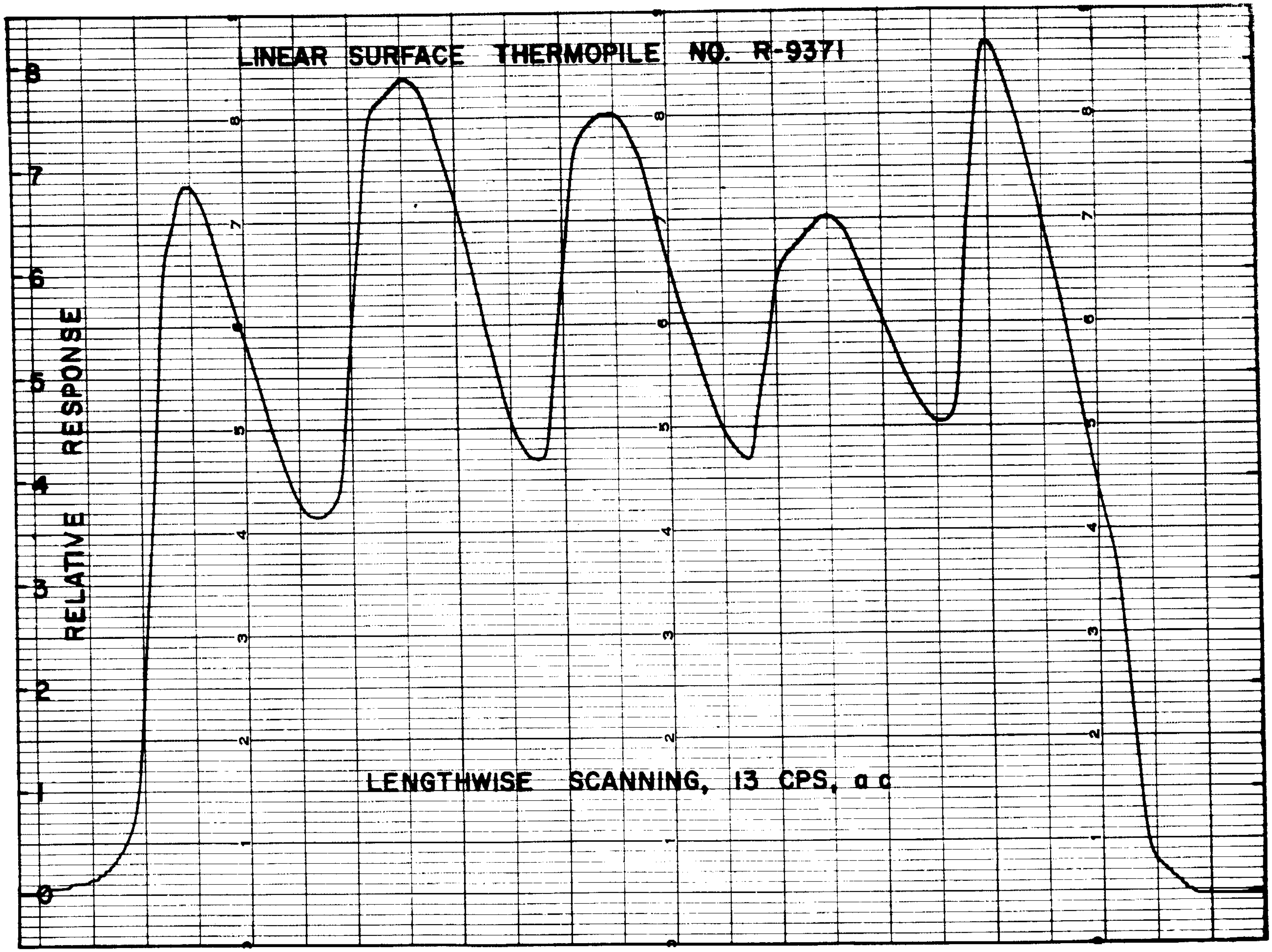


Fig. 2. Variations in sensitivity along thermopile R-9371 as indicated when the ac output is measured with the light flux chopped at 13 cps.

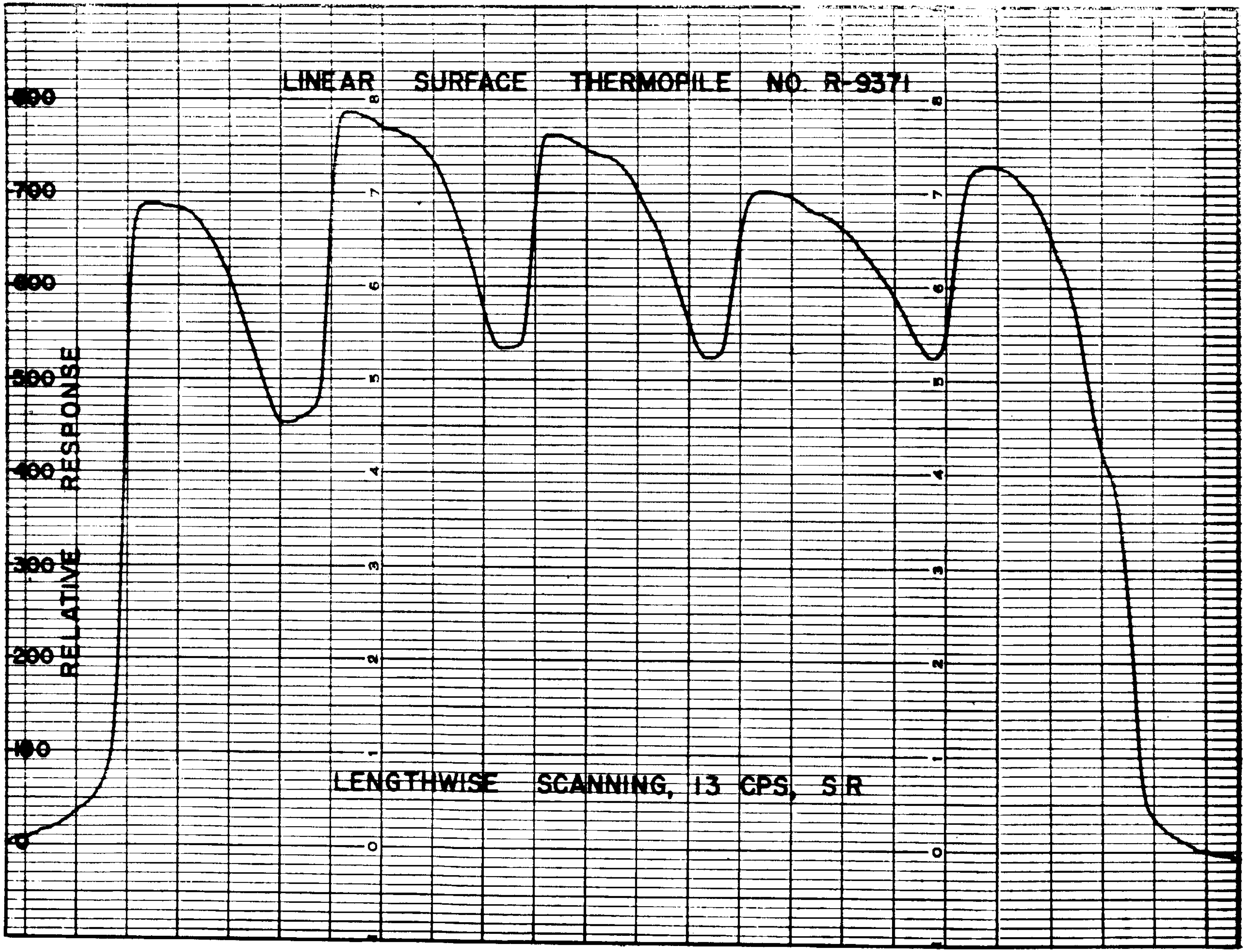


Fig. 3. Variations in sensitivity along thermopile R-9371 as indicated when the ac output is amplified and measured after synchronous rectification, with the light flux chopped at 13 cps.

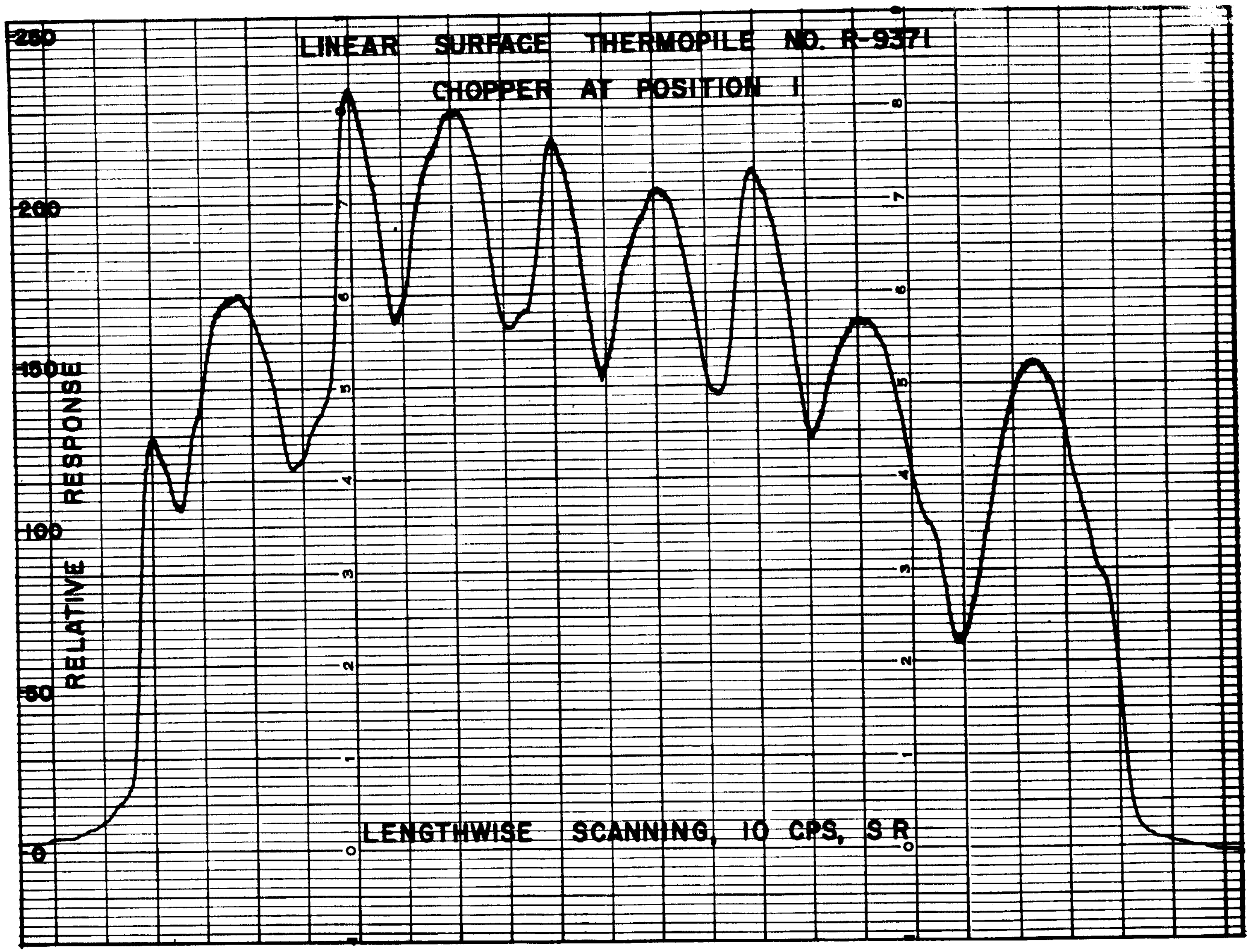


Fig. 4. Same as figure 3 except that the light flux is chopped at 10 cps.

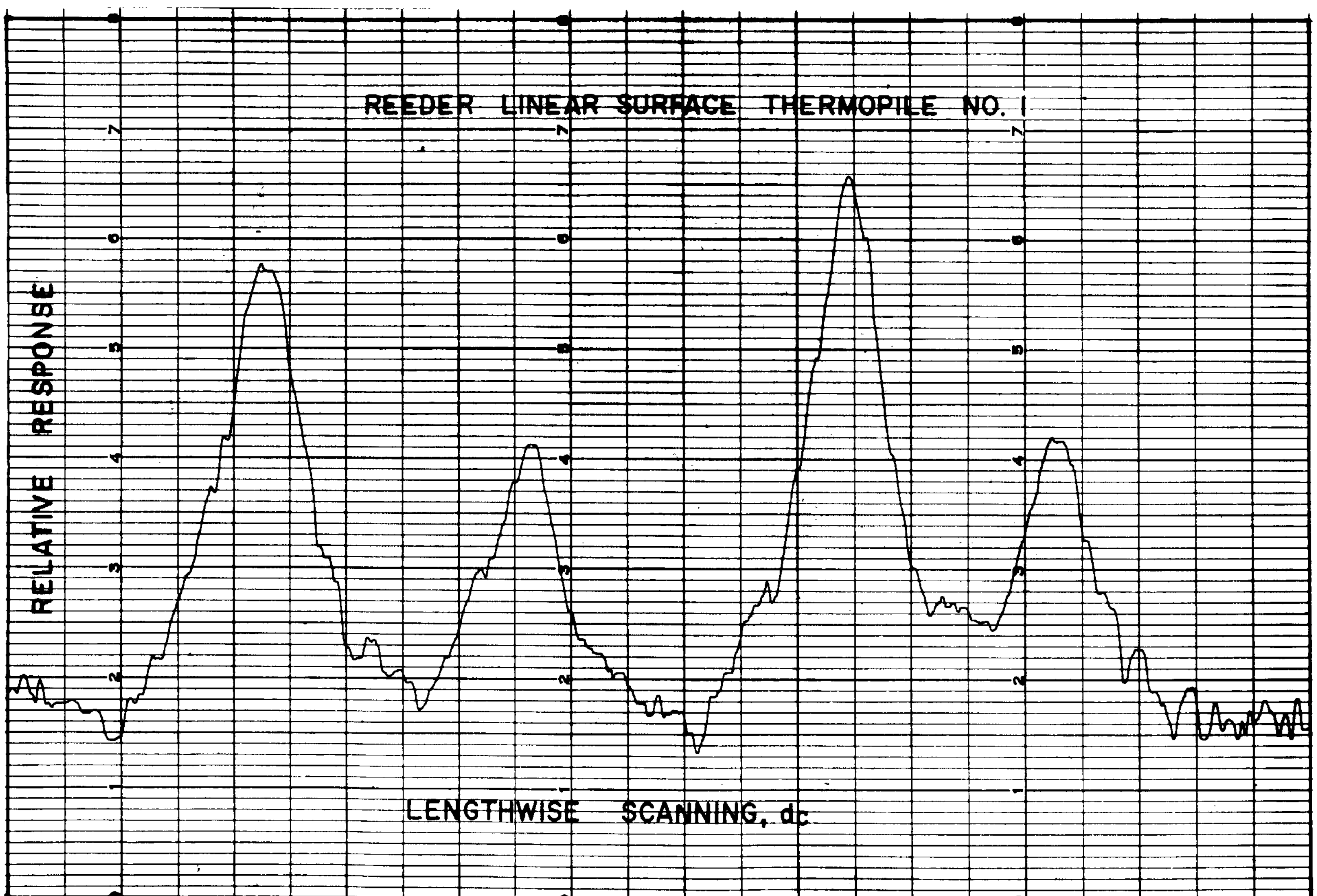


Fig. 5. Variations in sensitivity along thermopile R-1 as indicated when the dc output is measured

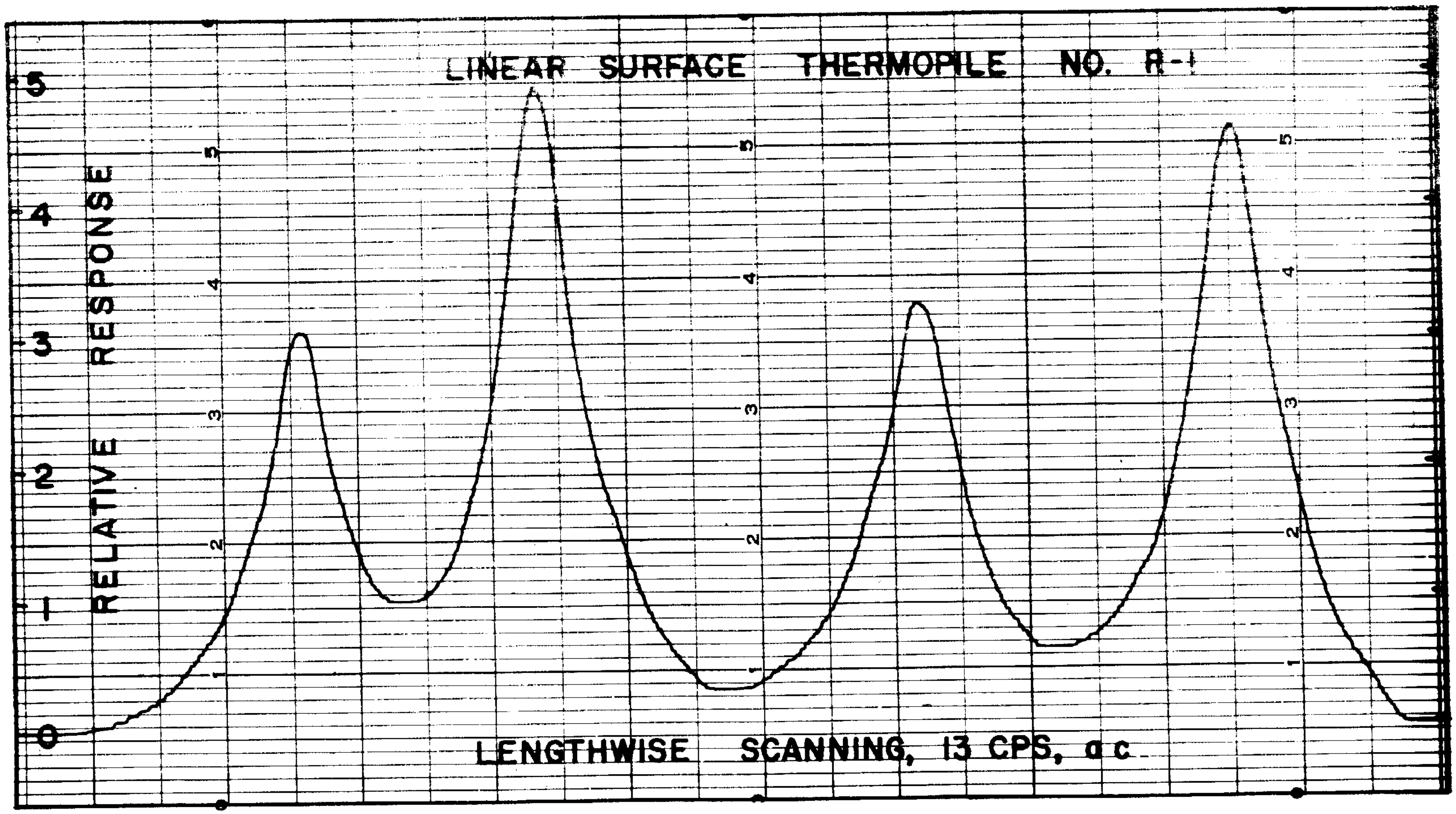


Fig. 6. Variations in sensitivity along thermopile R-1 as indicated when the ac output is measured with the light flux chopped at 13 cps.

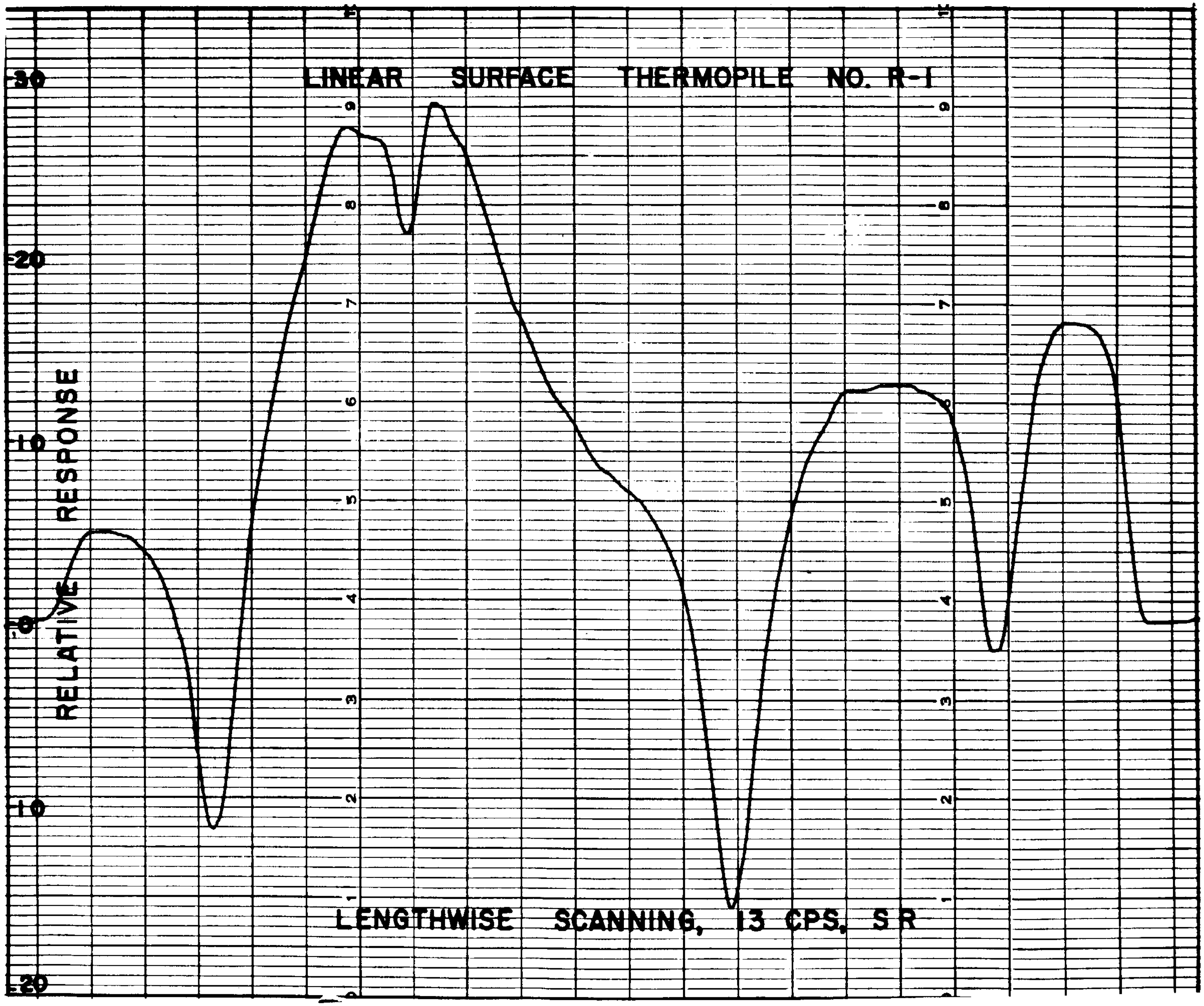


Fig. 7. Variations in sensitivity along thermopile R-1 as indicated when the ac output is amplified and measured after synchronous rectification, with the light flux chopped at 13 cps.

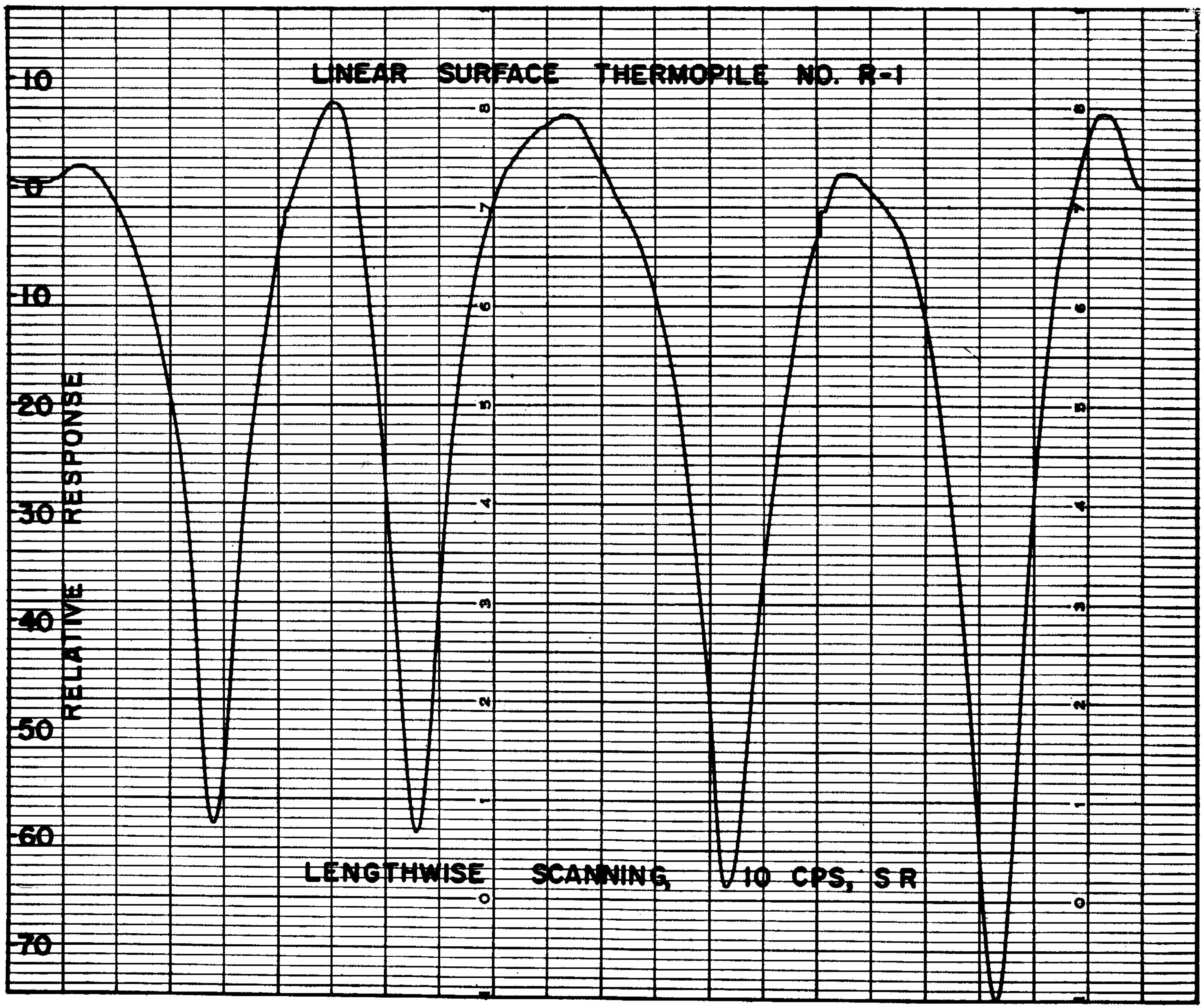


Fig. 8. Same as figure 7 except that the light flux is chopped at 10 cps.

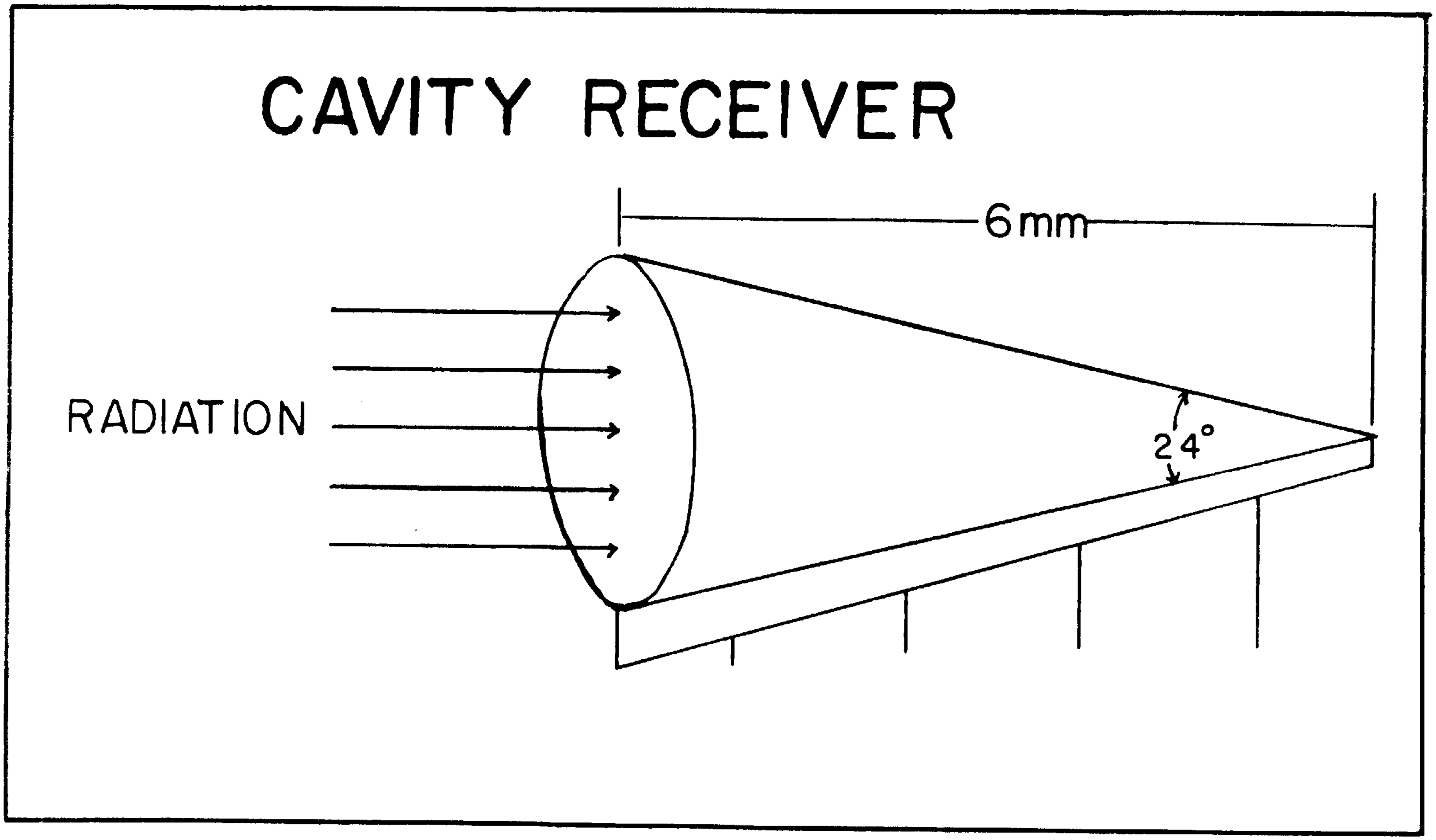


Fig. 9. Gold foil conical cavity detector.

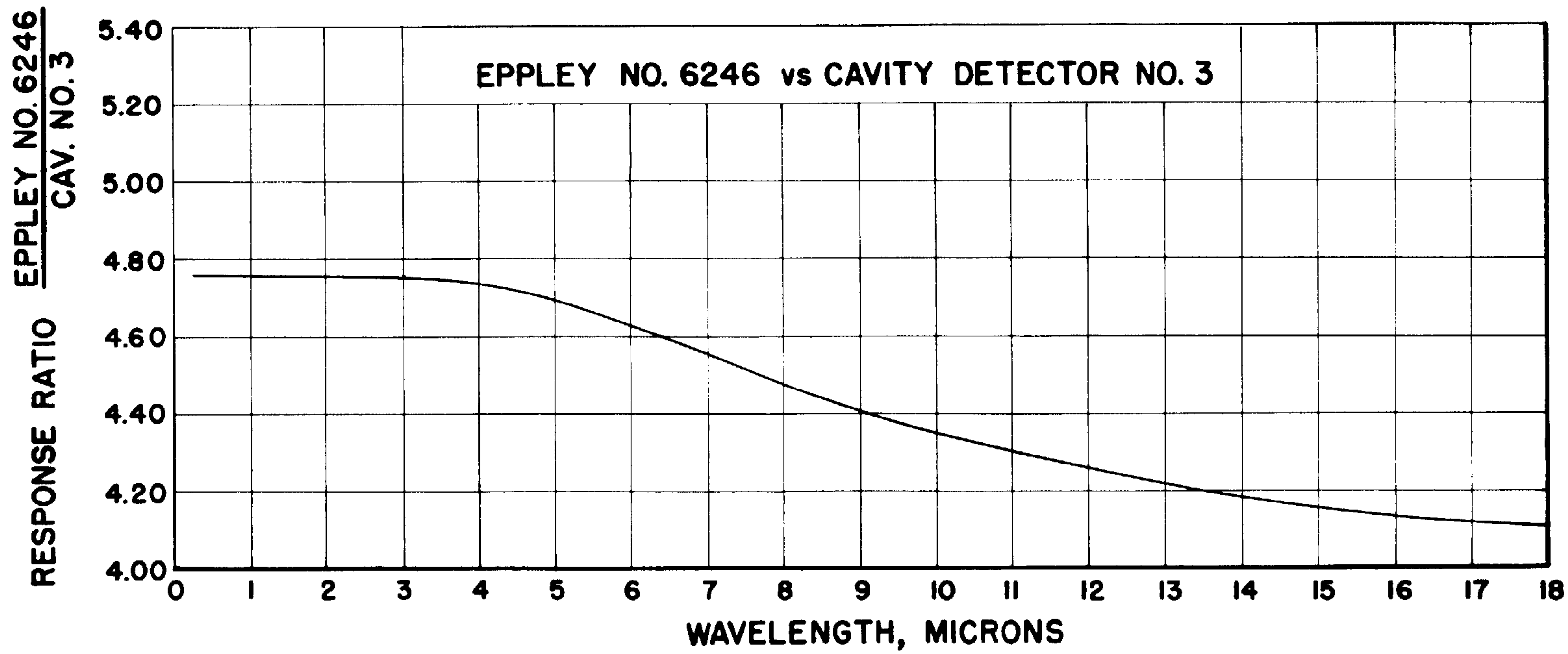


Fig. 10. Relative spectral response of a lamp black coated thermopile (Eppley No. 6246) as compared with cavity detector No. 3.

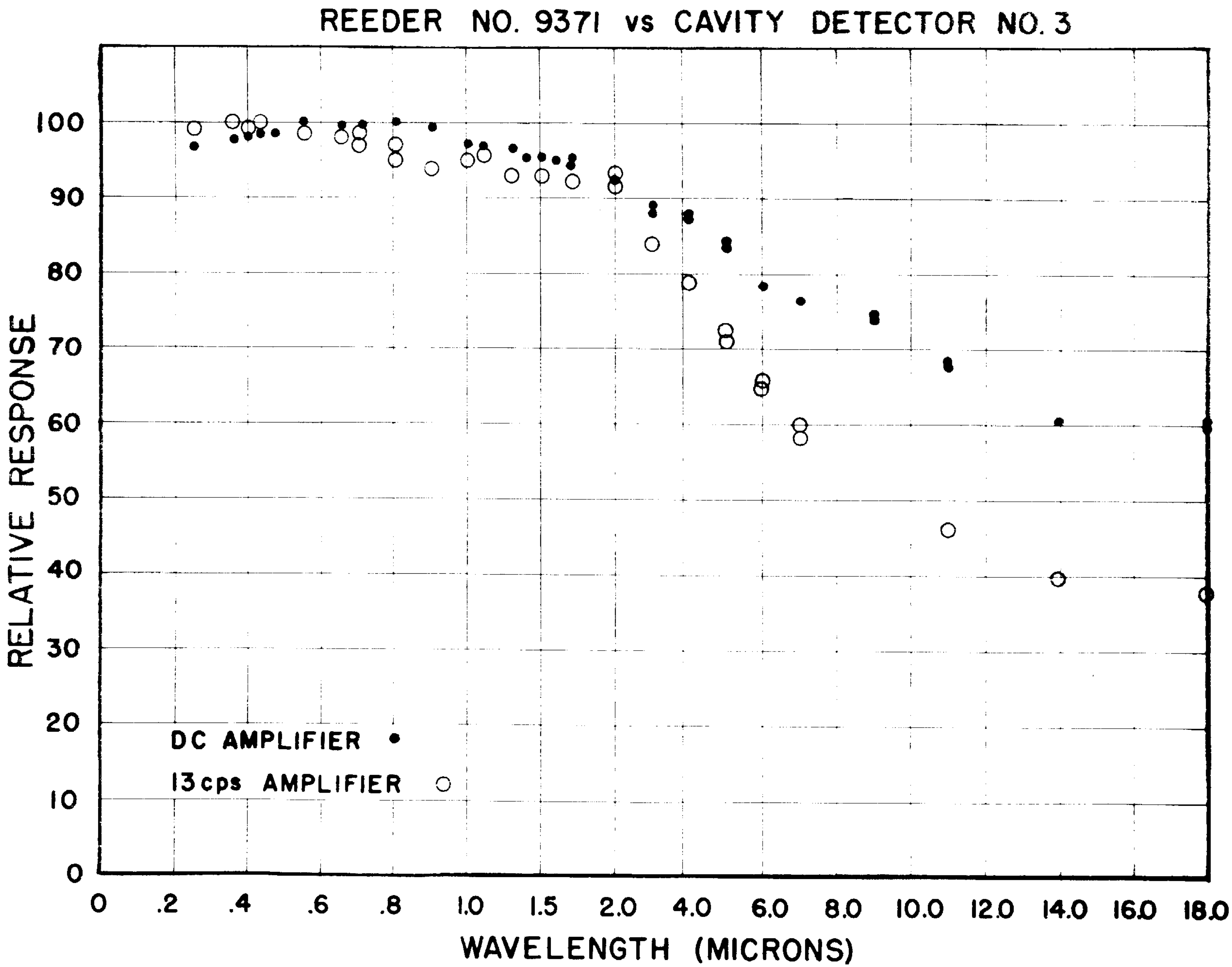


Fig. 11. Relative spectral response of a gold black coated thermopile (Reeder No. 9371) as compared with cavity detector No. 3.

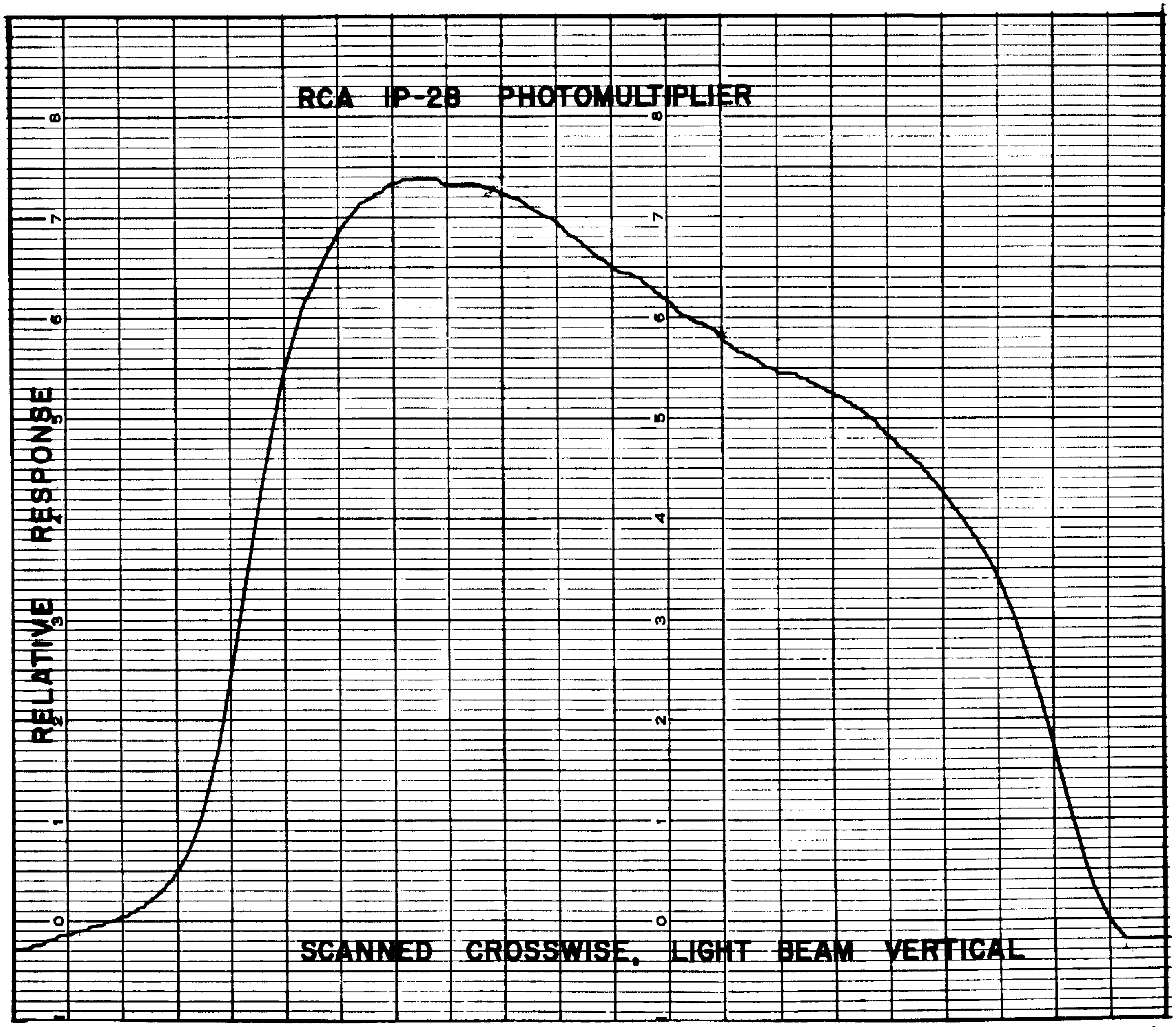


Fig. 12. Variations in sensitivity of an RCA 1P-28 photomultiplier for monochromatic light flux as indicated when the cathode is moved across the exit slit of a spectroradiometer.

12.

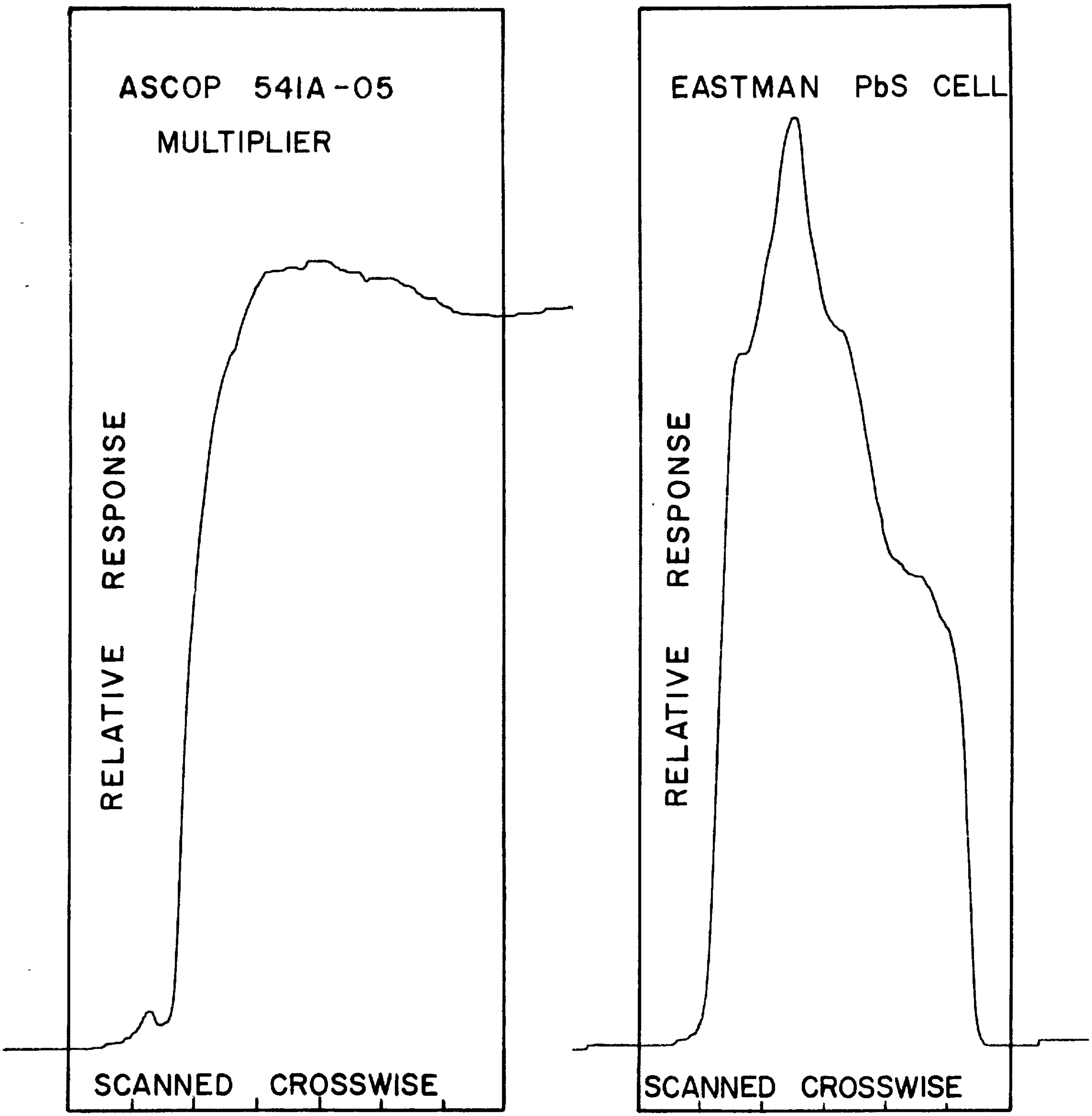


Fig. 13. Variations in sensitivity of an ASCOP type 541A-05 photomultiplier and of an Eastman PbS cell for monochromatic light flux as indicated when their cathodes are moved across the exit slit of a spectroradiometer. These two detectors form a pair to cover the spectral range from 0.25 to 2.6 microns. Adjustment is made so that each operates at the peak of maximum sensitivity.

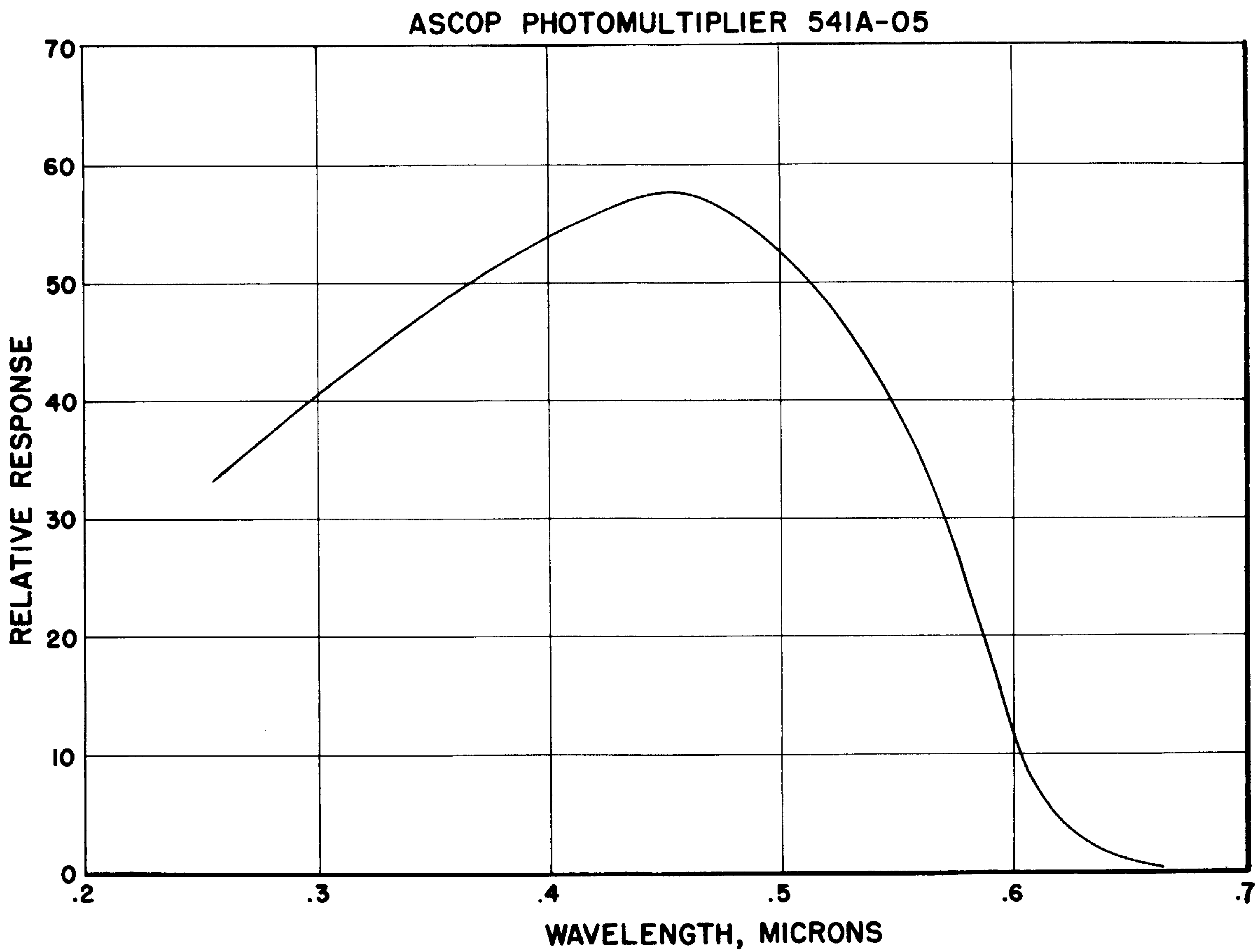


Fig. 14. Relative spectral response for equal energy of an ASCOP type 541A-05 photomultiplier (Manufacturers' data).

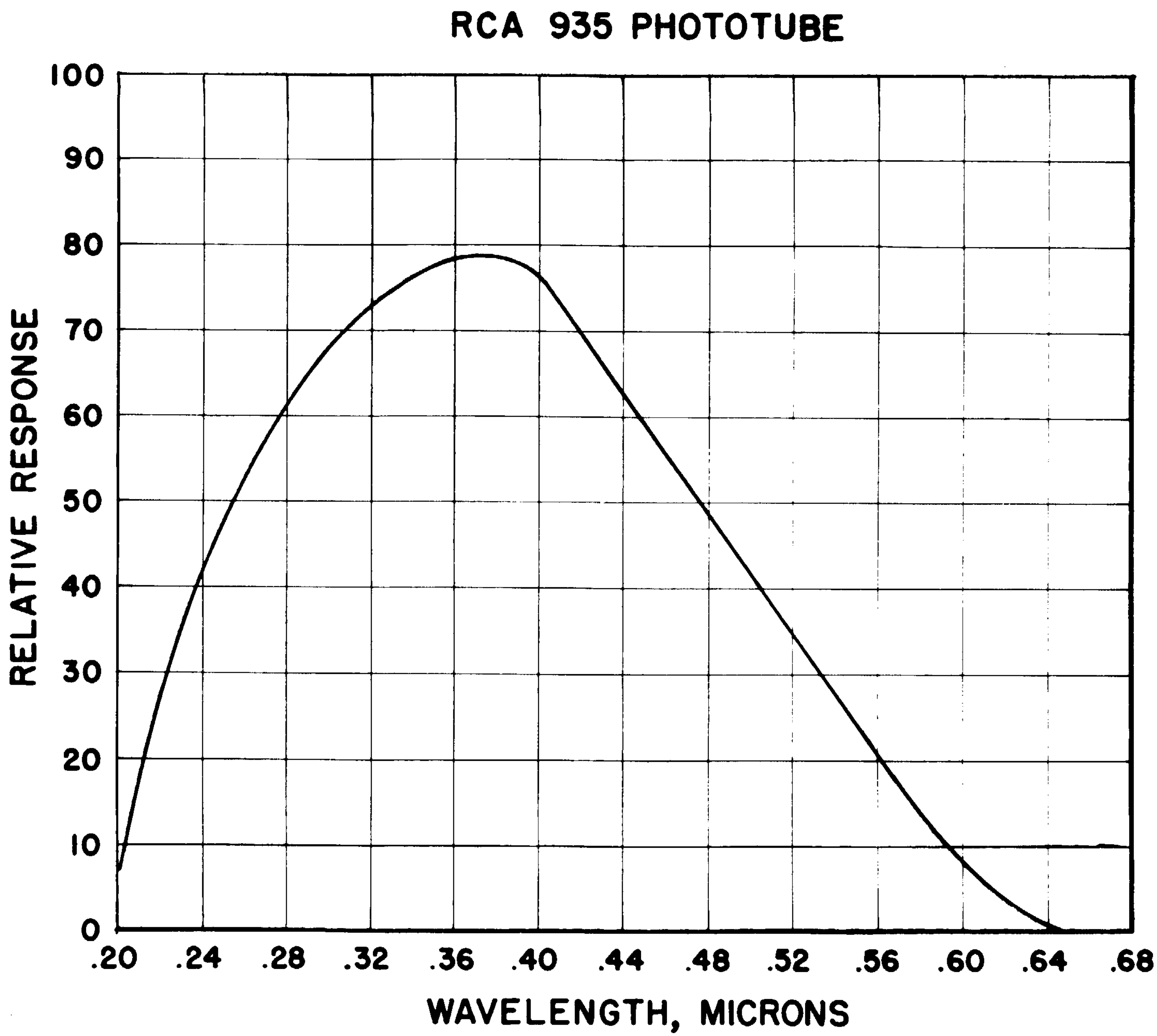
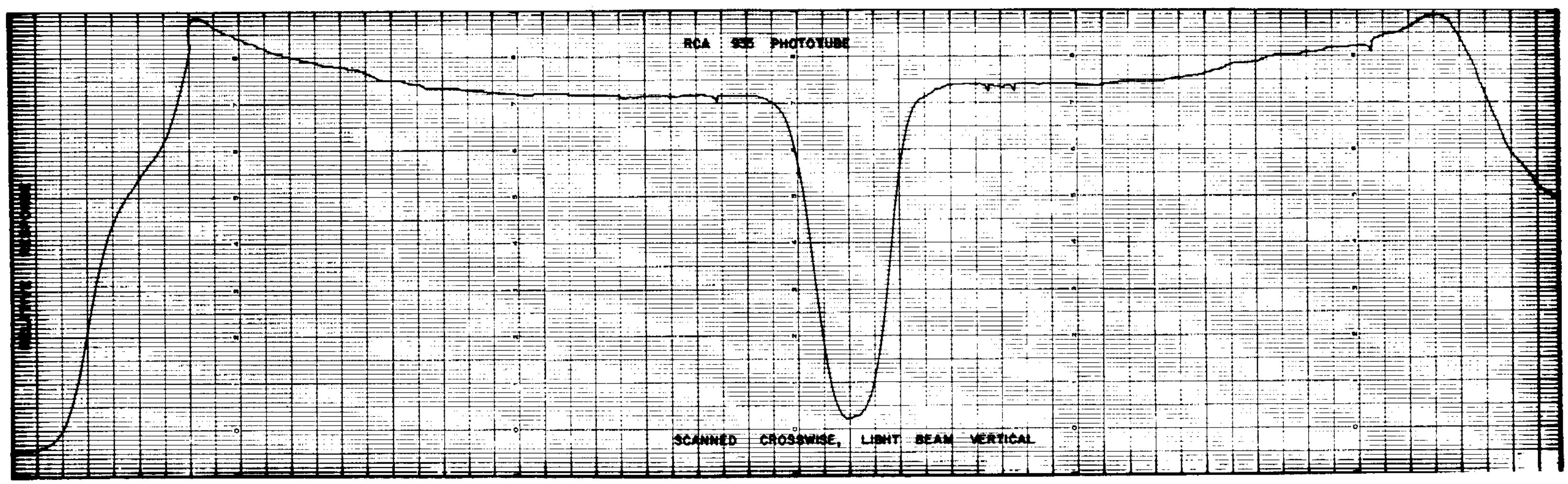


Fig. 15. Relative spectral response for equal energy of an RCA type 935 phototube (NBS data on tube 935-1).



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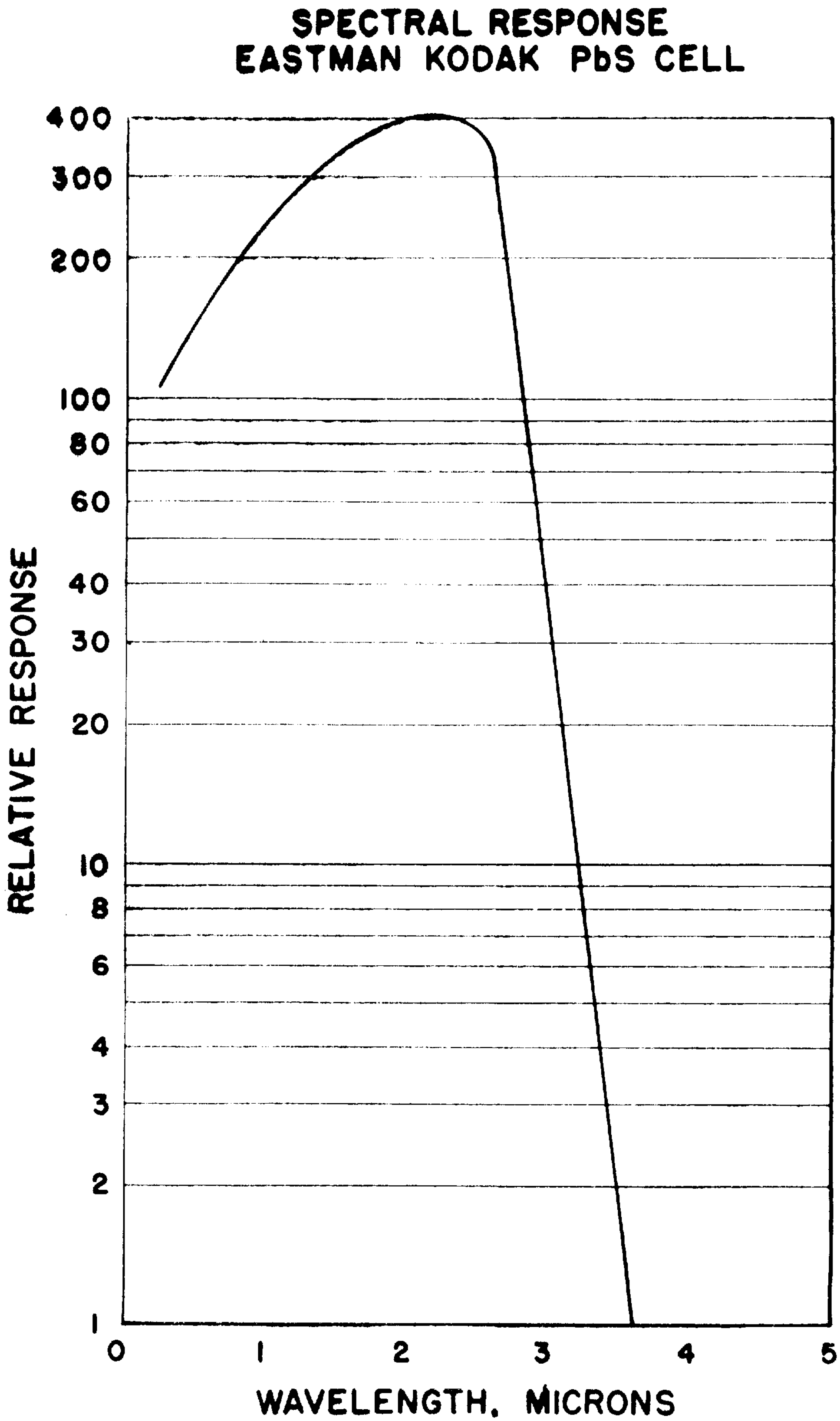

Fig. 17. Relative spectral response of an Eastman Kodak PbS cell (Manufacturers data).

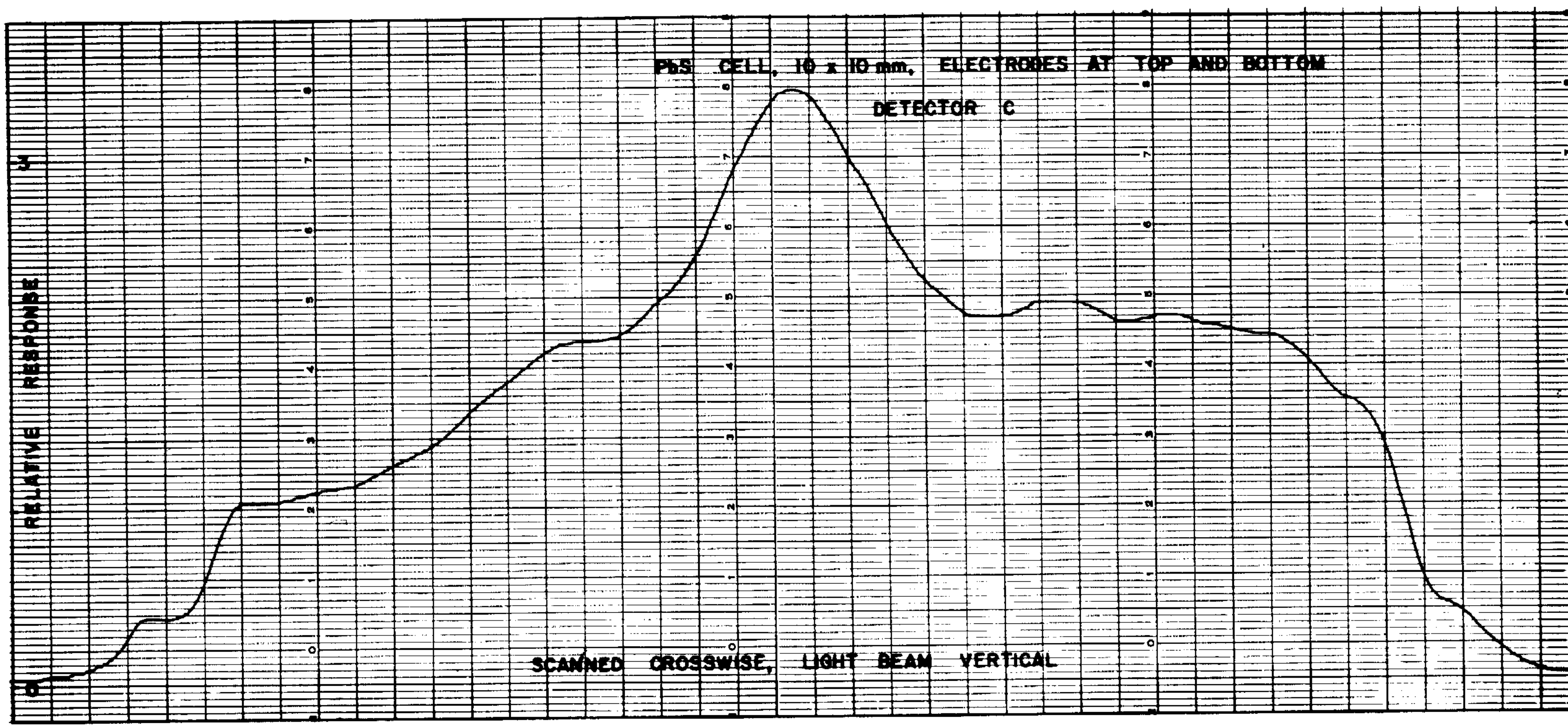

Fig. 18. Variations in sensitivity for monochromatic light flux as indicated when the PbS cell is moved across the exit slit of a spectroradiometer. For this illustration the electrodes were at the top and bottom of the spectrometer slit.

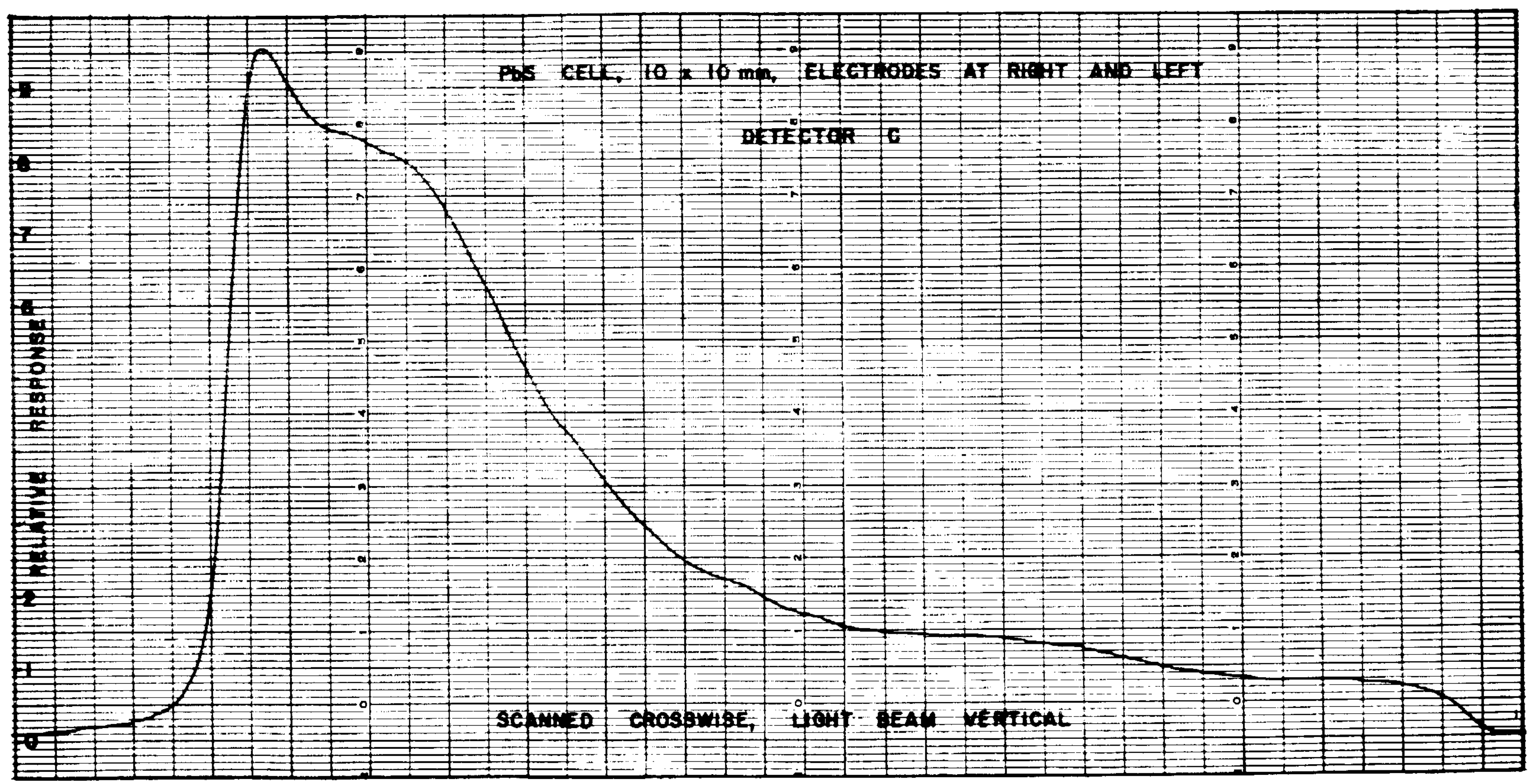

Fig. 19. Same as figure 18 except that cell was rotated 90° thus placing the electrodes at right and left sides of slit respectively.

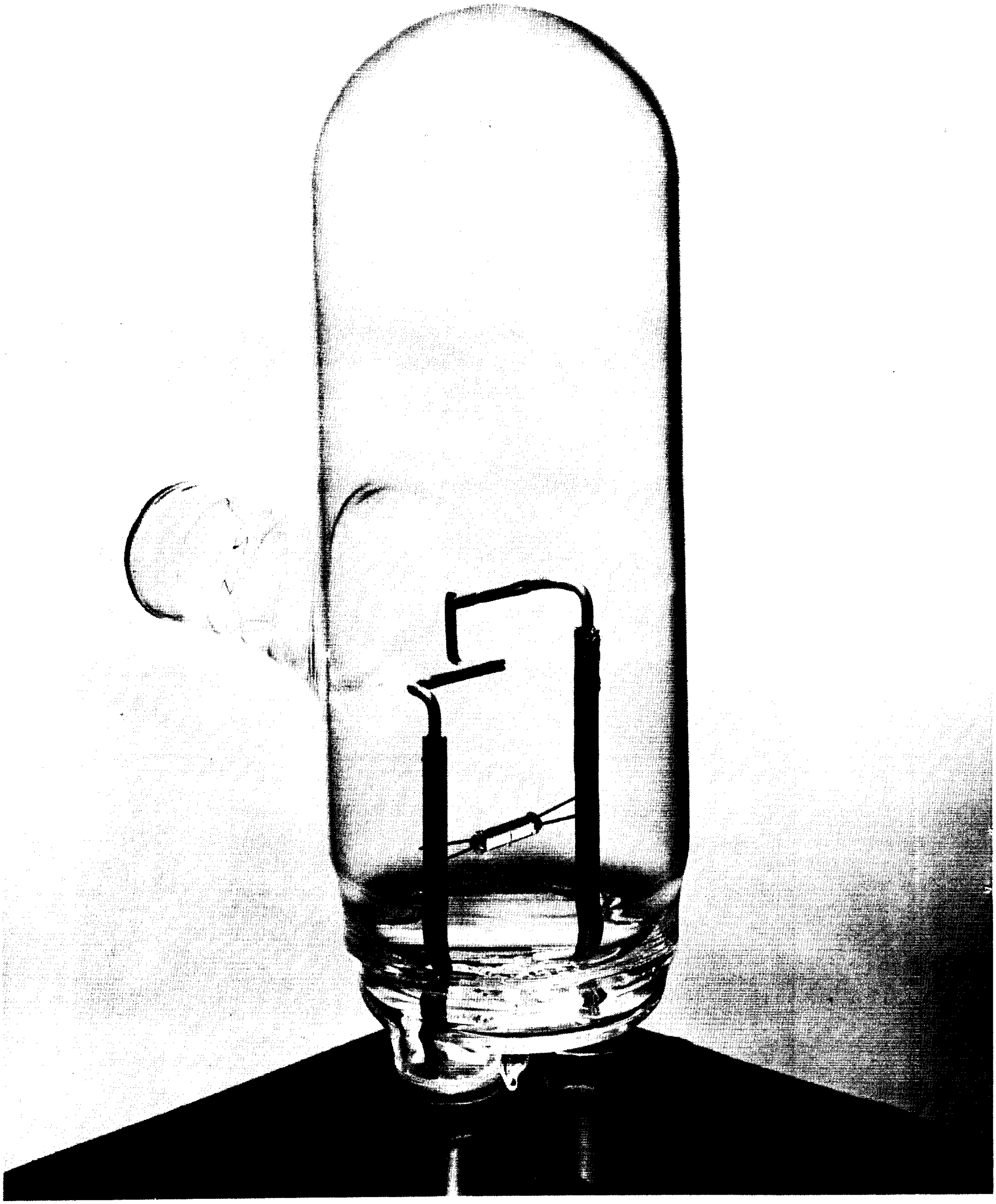

Fig. 20. Tungsten ribbon strip lamp standard of spectral radiance.

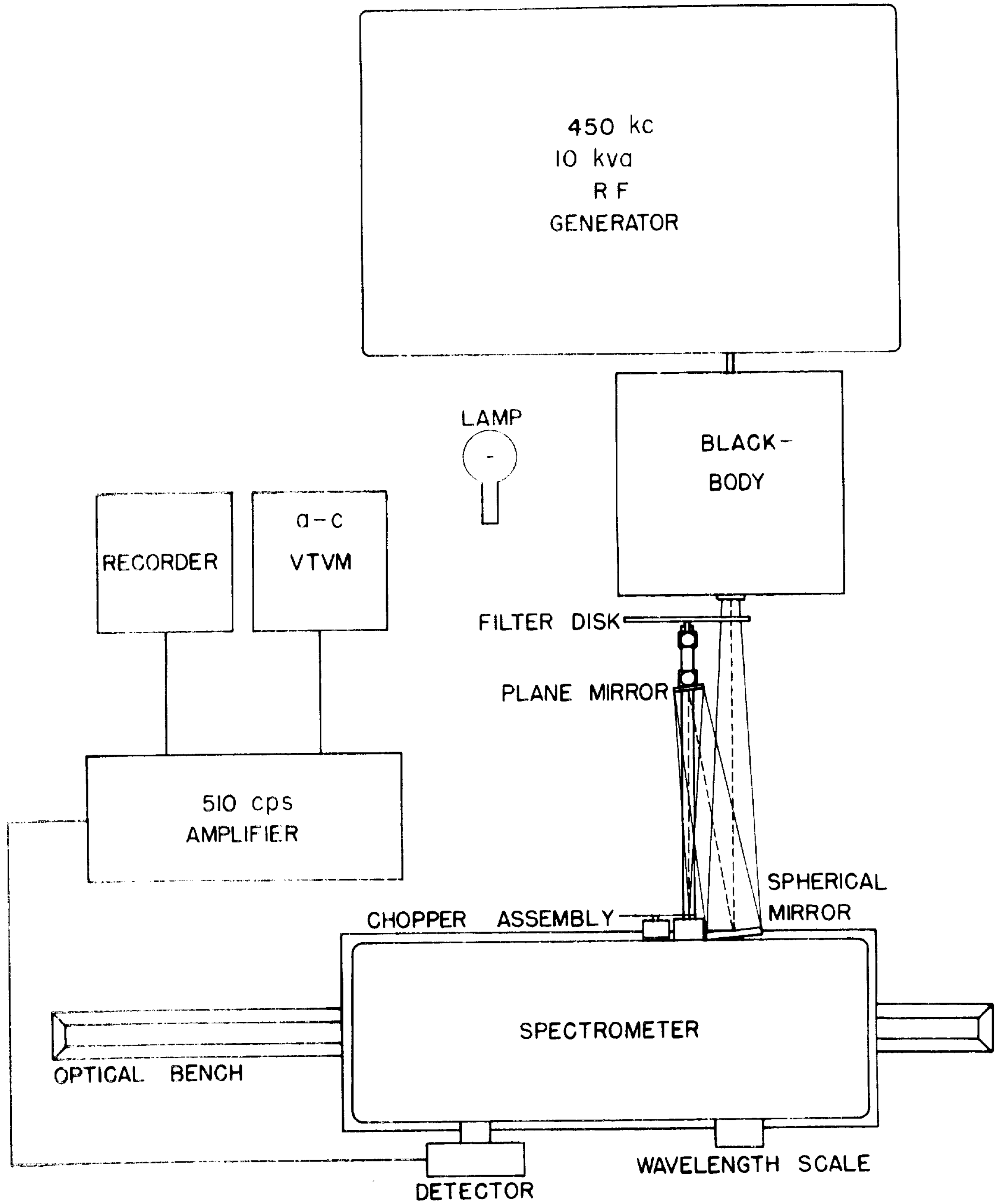

Fig. 21. Block diagram showing the instrumental setup of blackbody, monochromator, lamp, and associated equipment employed in the calibration of the NBS standard of spectral radiance for the wavelength region of 0.25 to 0.75 micron.

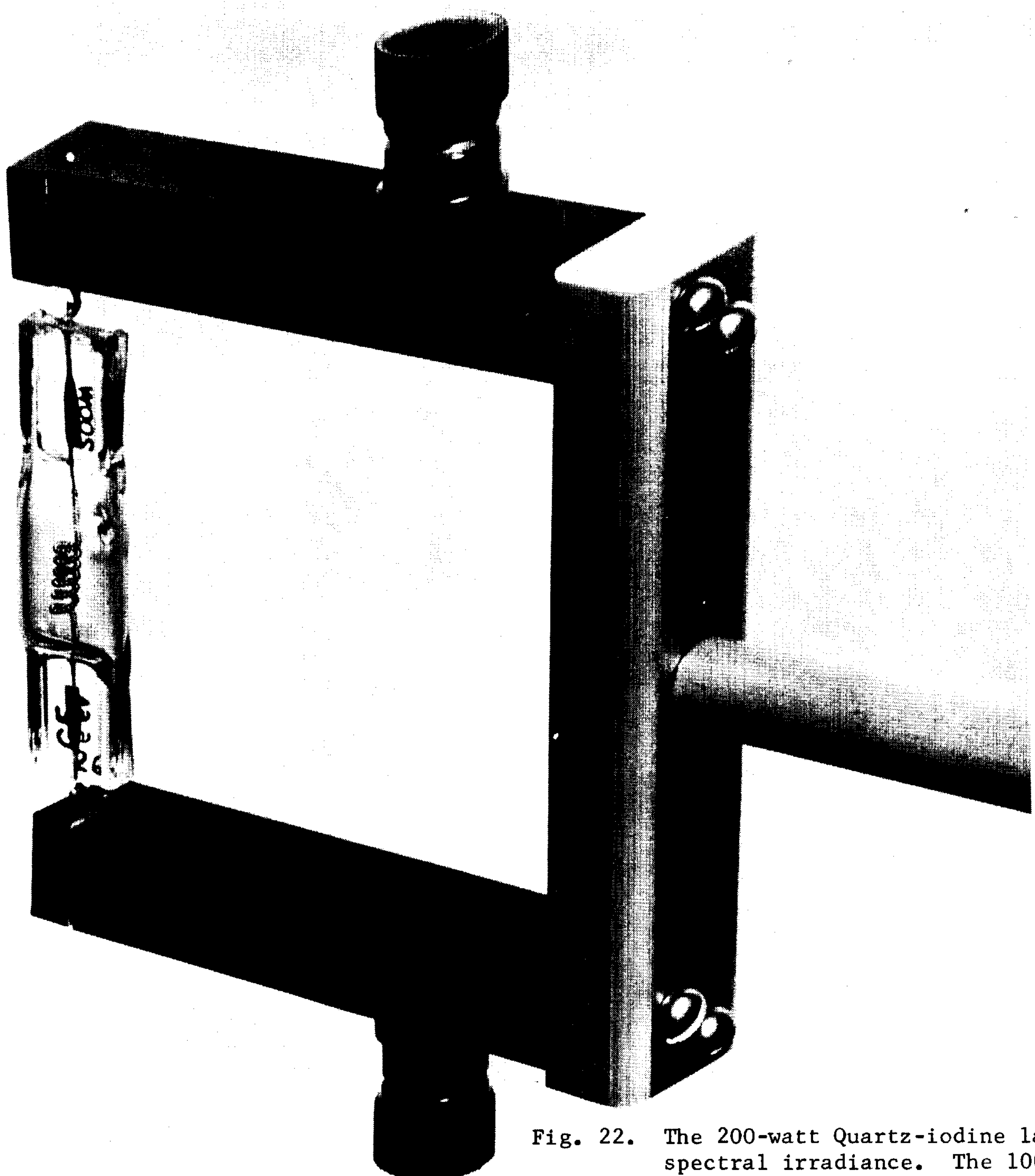

Fig. 22. The 200-watt Quartz-iodine lamp standard of spectral irradiance. The 1000-watt standard is of similar appearance and is mounted in a similar holder.

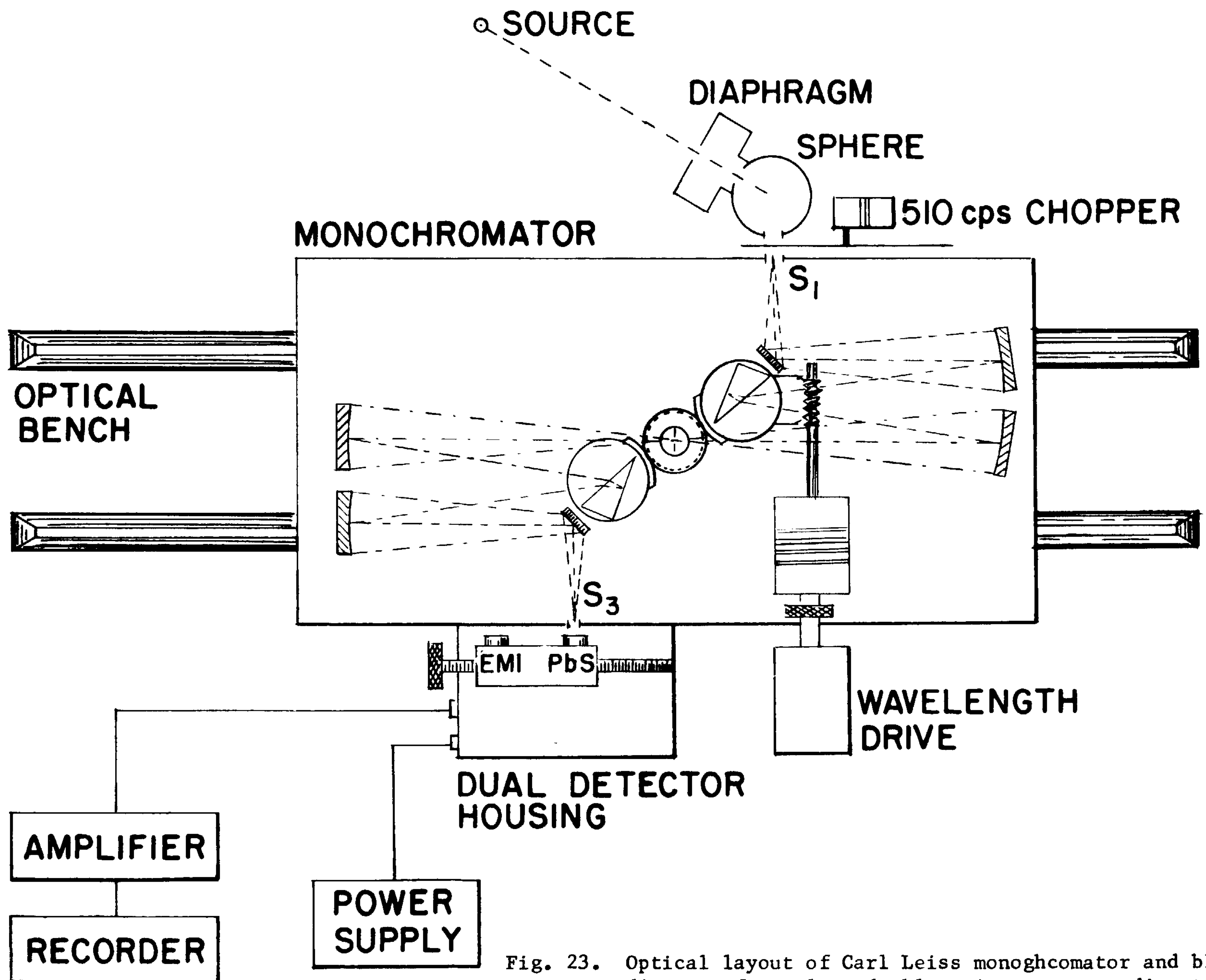

Fig. 23. Optical layout of Carl Leiss monoghcomator and block diagram of complete double prism spectroradiometer employed in solar simulator measurements.

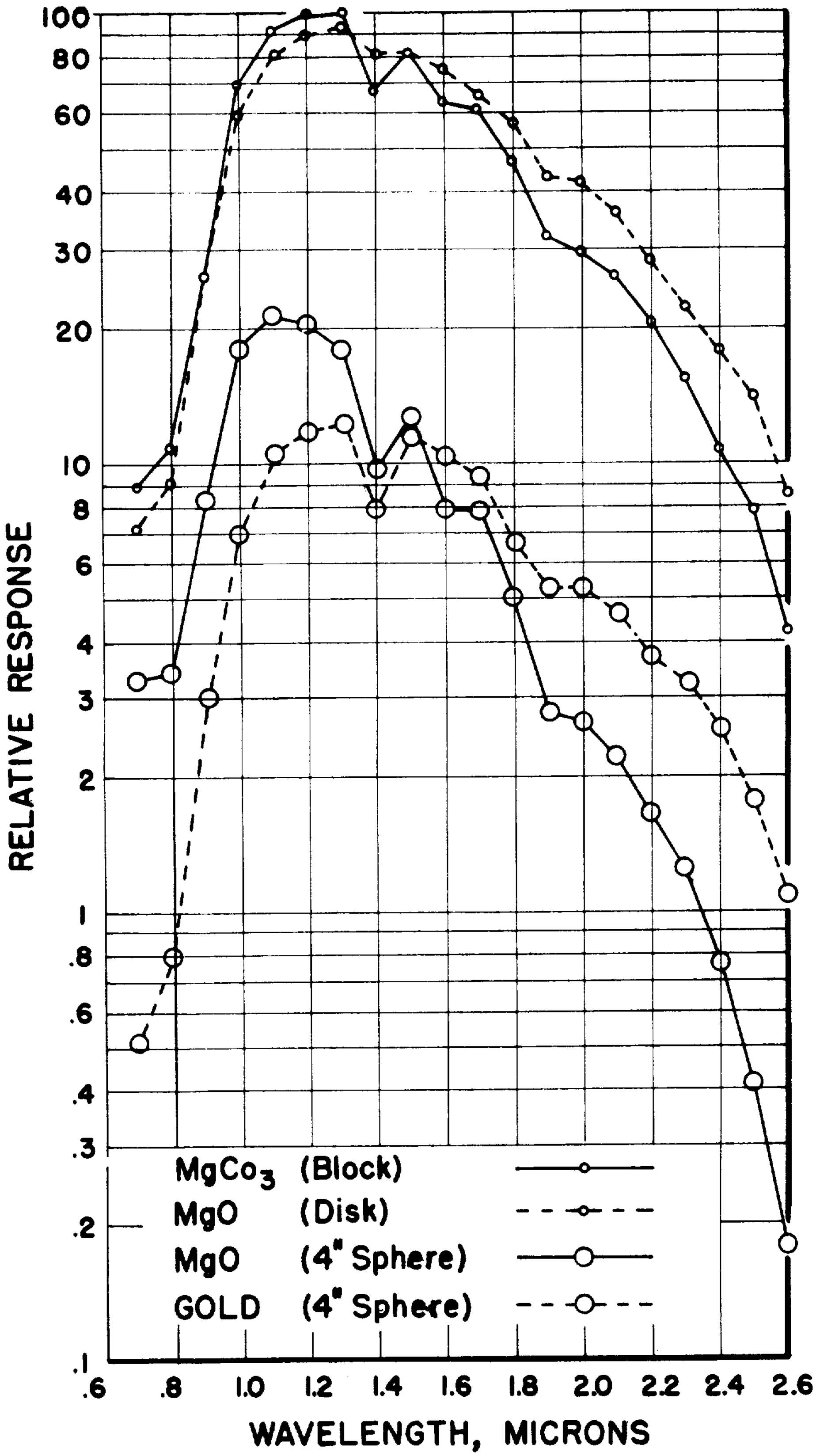

Fig. 24. Relative efficiencies in the infrared spectrum of four diffusers when used in combination with the Carl Leiss spectroradiometer when employing an Eastman Kodak PbS cell as detector and a 1000-watt iodine lamp as source.

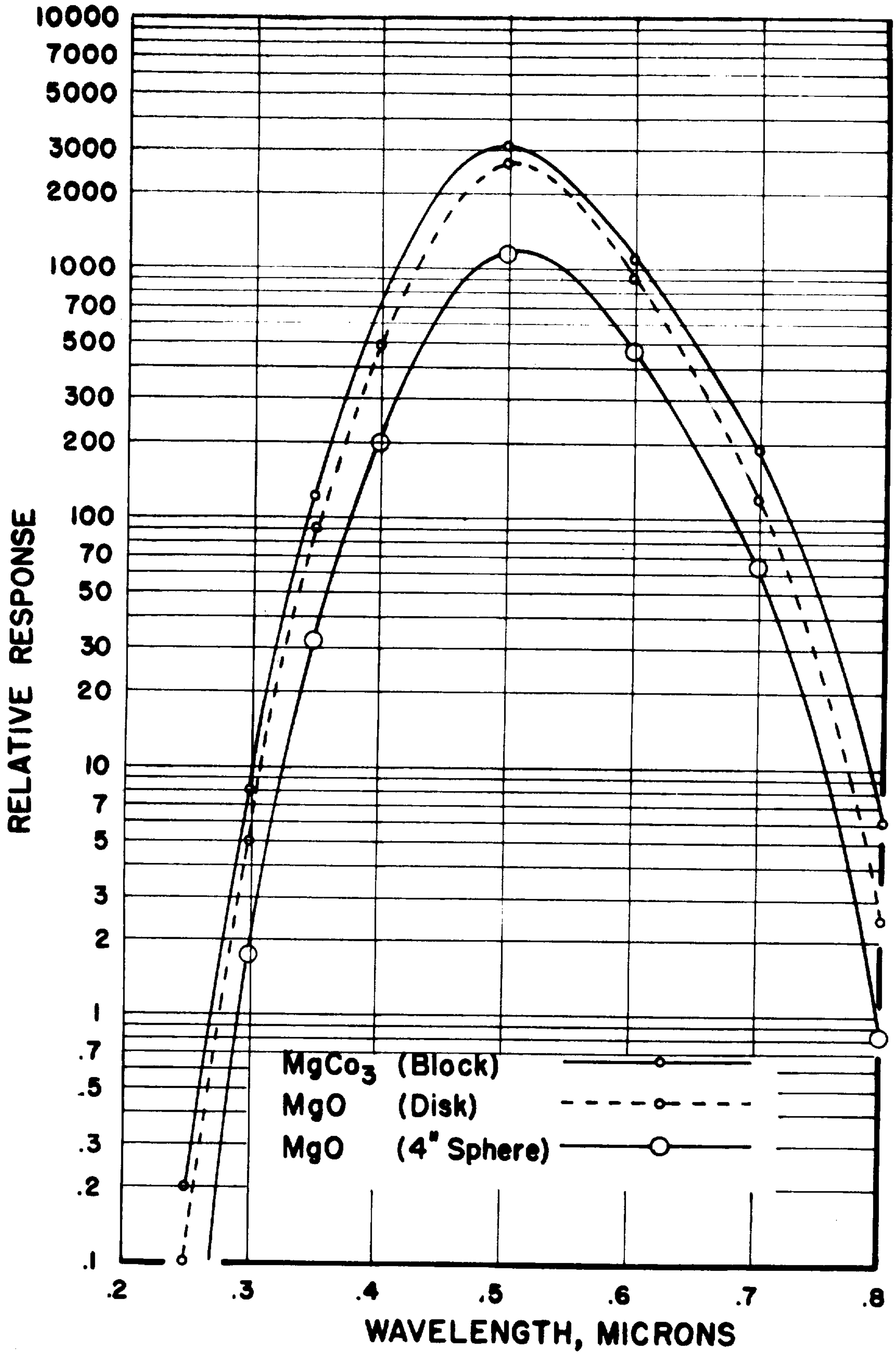

Fig. 25. Same for the ultraviolet and visible spectrum as in figure 24 for the infrared except in this case the detector is an EMI type 6256B photomultiplier and the peak value is again arbitrarily set near 3000.

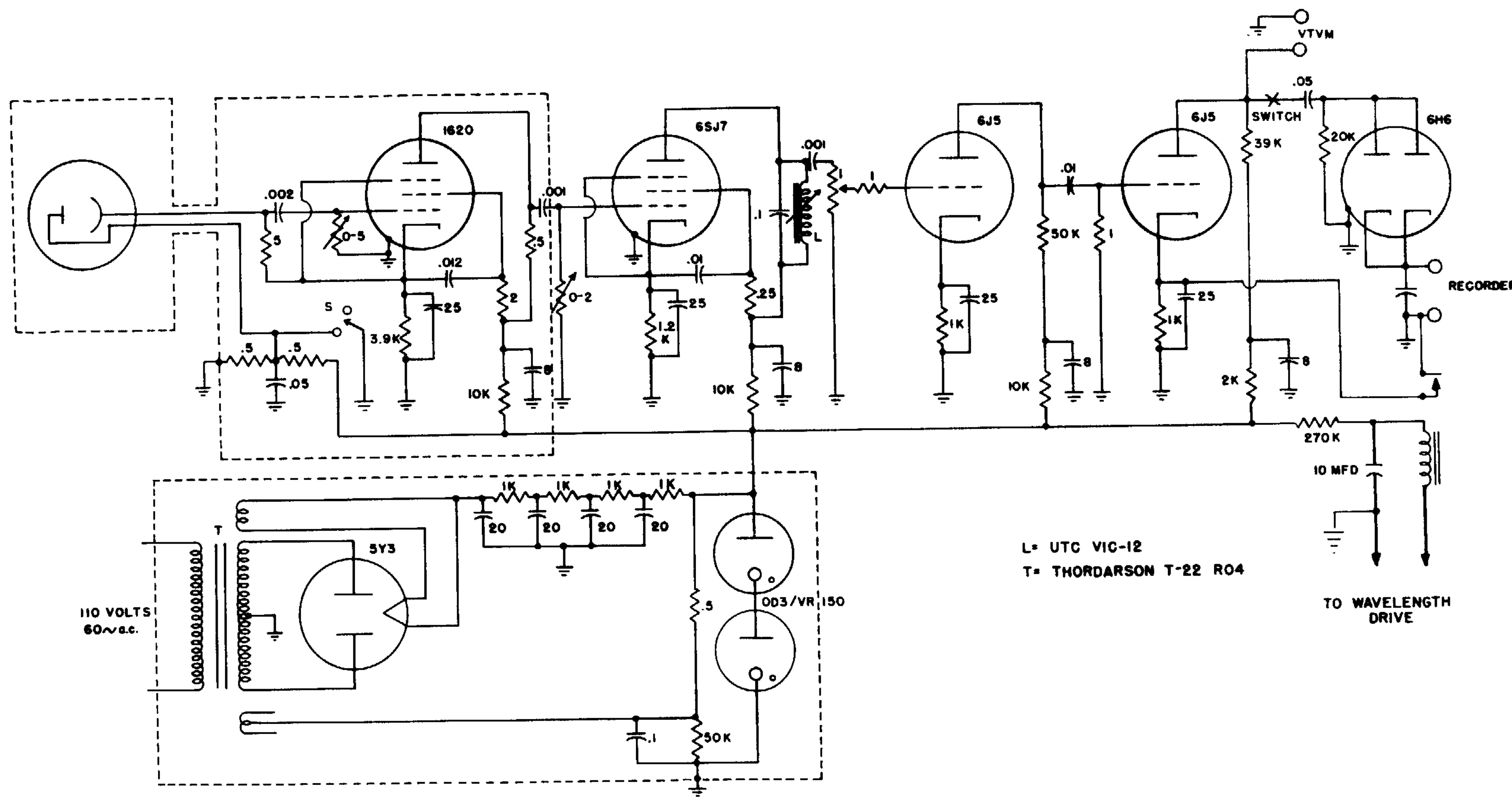

Fig. 26. Electronic circuit employed in the 510-cycle-per-second tuned amplifier. Resistances are in megohms and capacitances are in microfarads except as otherwise noted.

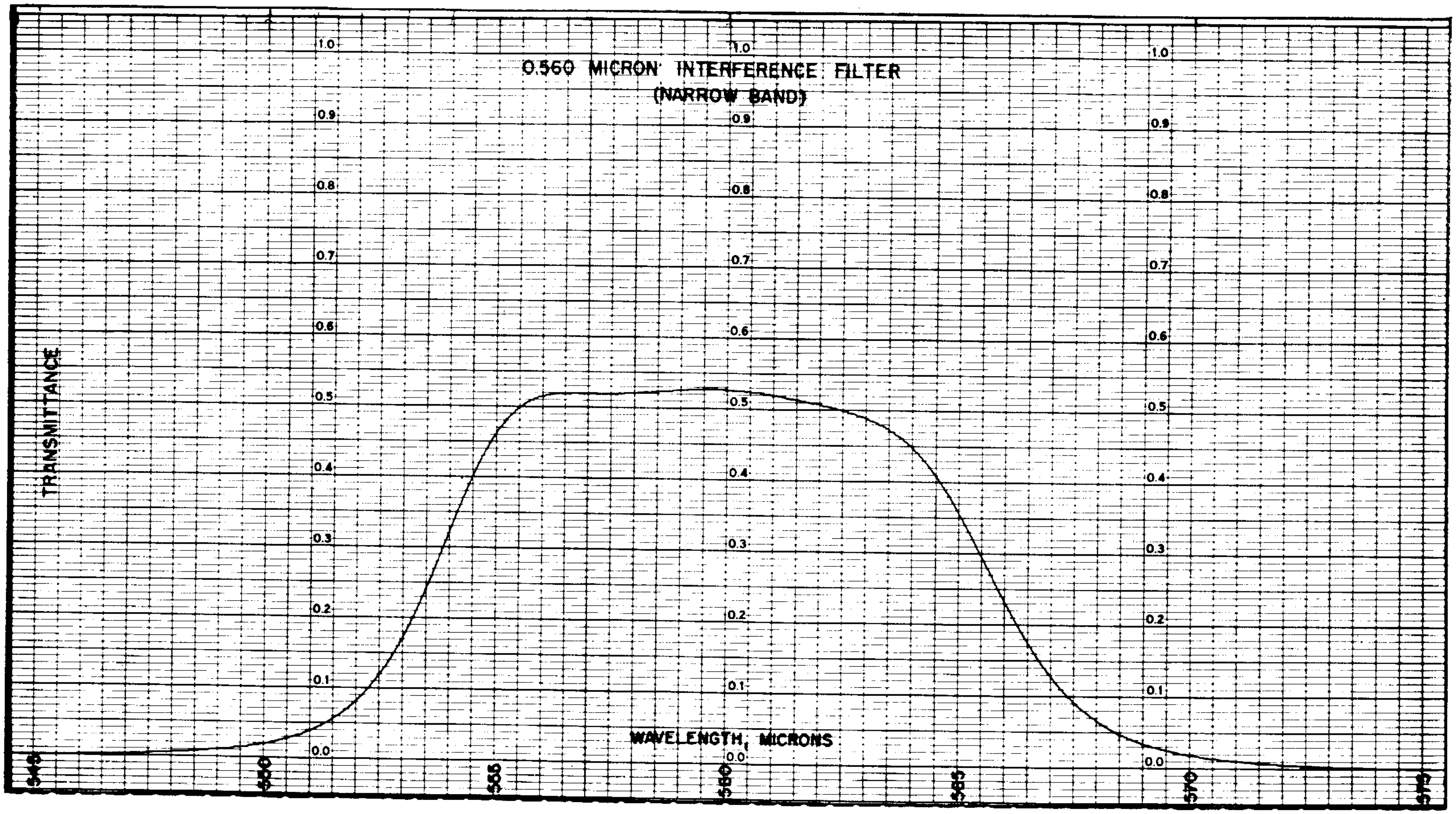

Fig. 27. Spectral transmittance of the 0.560 micron narrow-band interference filter as obtained on a Cary-Model 14R spectrophotometer.

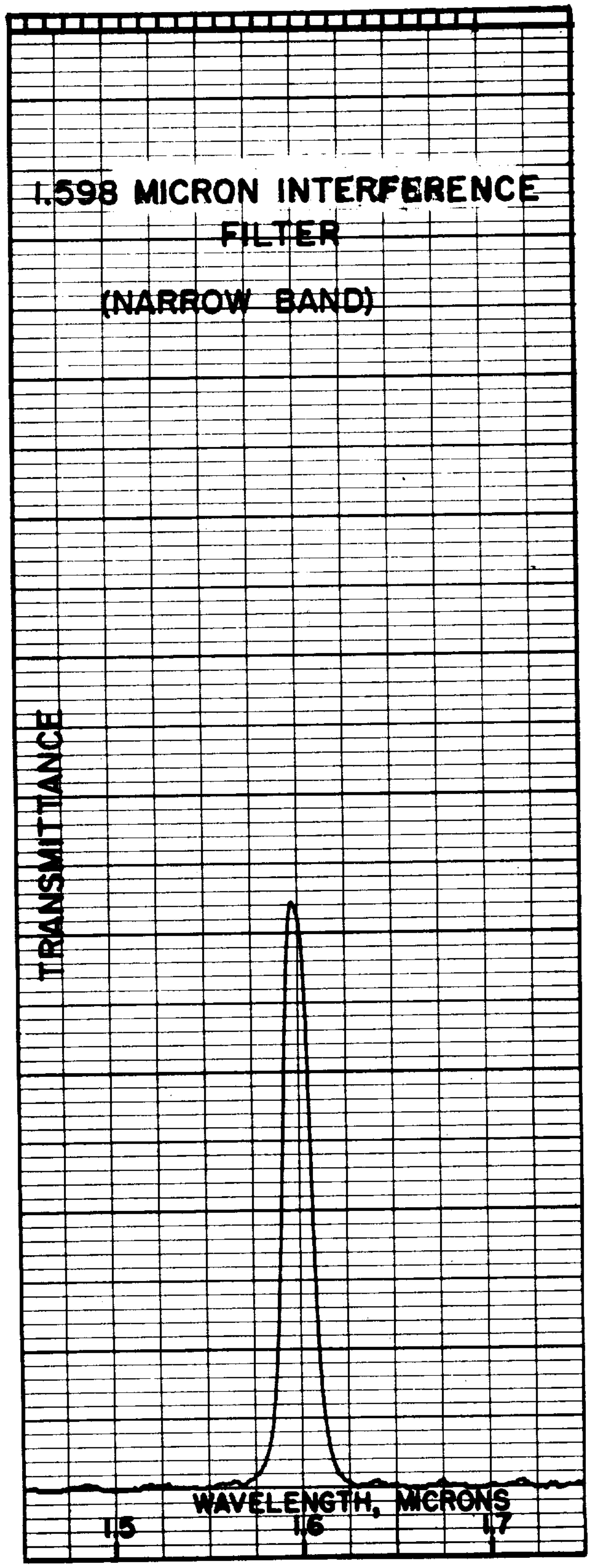

Fig. 28. Spectral transmittance of the 1.598 micron narrow-band interference filter as obtained on a Cary Model 14R spectrophotometer.

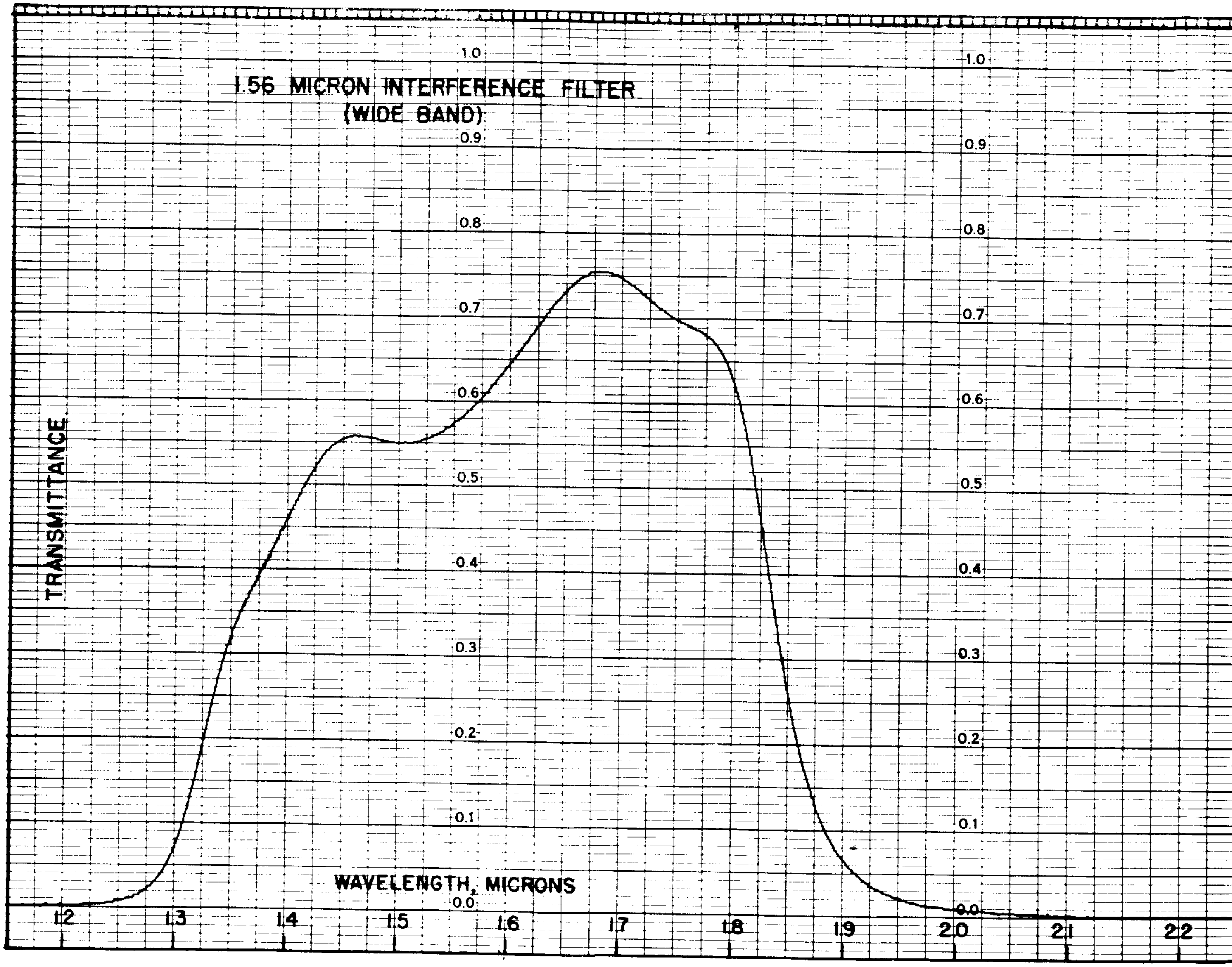

Fig. 29. Spectral transmittance of the 1.56 micron wide-band interference filter as obtained on a Model 14R spectrophotometer.